Copyright 1940, by the AMERICAN SOCIETY OF NAVAL ENGINEERS.

JOURNAL

OF THE

AMERICAN SOCIETY OF NAVAL ENGINEERS

VOL. 52. NOVEMBER 1940. No. 4

The Society as a body is not responsible for statements made by individual members

COUNCIL OF THE SOCIETY

(Under whose supervision this number is published).

Rear Admiral HENRY WILLIAMS, U.S.N.
Captain H. M. COOLEY, U.S.N.
Captain LYBRAND P. SMITH, U.S.N.
Commander F. W. PENNOVER, JR., U.S.N.
Commander E. E. BRADY, U.S.N.
Comdr. CHARLES J. ODEND'HAL, U.S.C.G.
Mr. GEORGE B. FERRIER
Mr. HAROLD K. BECK
Commander JAMES E. HAMILTON, U.S.N.

THE WEIGHT FACTOR IN THE DESIGN OF RADIO EQUIPMENT FOR NAVAL AIRCRAFT.

BY LIEUT. (JG) WM. B. WELLS, U. S. N. R.

The author here presents the first part of a two part article. The subject, touching as it does the fields of both radio design and aeronautics, is of timely interest to naval engineers. In part one, the author devotes his technical discussion largely to the affect of antenna design on his subject. The second part will cover other factors.

PART ONE.

Recent events have vastly altered the "modern" but conservative concepts of a few years ago in regard to Naval aircraft radio, and what then were mere trends have today frozen into vital and

urgent necessities. The general trend, though modified, still remains but has presently acquired an imperative acceleration which has compelled "streamlining."

The importance of weight reduction in modern military (naval) aircraft installations can hardly be over-emphasized. It has been stated that every pound added to the installation in an aircraft causes indirectly the addition of another 3 pounds distributed between wing structure, propeller, and fuel. On the other hand, the importance of radio equipment to successful military aircraft operations is being amply demonstrated daily.

Rapid strides had been made in the design of radio equipment for Naval aircraft in the past, and valuable developments and improvements have been accomplished within recent years. Aircraft radio design has never really been static nor dormant. Nor has airplane design. Nevertheless, only within the past year has the military advantage, and, indeed, necessity of adequate armor and armament on military aircraft been forcefully recognized. Advancements in aircraft design have not been accompanied by correspondingly spectacular improvements in aircraft radio equipment but this has been occasioned in no small degree by the growing handicaps under which the struggling radio designer has labored. With the advent of armored and heavily armed, high performance aircraft, a reduction and reallocation of permissible weights within the airplane, particularly the fighter types, has become a paramount problem.

A corollary to this problem is that if the weight of past and existent aircraft radio installations is satisfactory and innocuous, or at least not prohibitive, from the standpoint of present aircraft design and performance, the later radio equipments will provide more performance in the same weight. The allowable weights of Naval aircraft radio equipment have been largely determined by what has been obtained in the past for aircraft communication apparatus. This has been because the minimum possible weights for a given performance have not heretofore been readily predictable even on an empirical basis. With the accumulation of experience and improvements in manufacturing technique such predictions or reliable estimates have become possible. In practice,

both lines of attack have been employed in the design of equipment; i.e., an attempt to reduce the weight of the airplane's radio installation while at the same time augmenting and improving the equipment's performance. The two requirements are obviously conflicting and become somewhat, though not entirely, incompatible from a design standpoint.

The distinction between aircraft radio equipment and that for surface and sub-surface craft is characterized primarily by the space and weight restrictions of the former and secondarily by the mode and types of operation in naval aircraft, and these differences are becoming more widely divergent as airplane combat performance is increased. Nevertheless, battleship radio performance has largely been brought into Naval aircraft, particularly in the larger airplanes of the patrol class, with due consideration to the operating requirements peculiar to such aircraft. Many and ingenious have been the devices to which radio equipment manufacturers have resorted in the effort to retain high performance and accessibility with reduced size and weight and greater rapidity and simplicity of operation. For the most part, however, the gross weight of radio installations in the larger airplanes has remained nearly fixed during the past several years while the equipment performance, including frequency coverage and general utility, has been increased. The actual radio load, including radio aids to air navigation, in any one airplane obviously depends upon such considerations as the size and fuel capacity of the airplane, its mission and the relative importance of radio thereto. By way of comparison, a naval airplane of the fighter type may carry 60 pounds of equipment devoted to radio whereas aircraft of the patrol class may carry as high as 500 pounds of such equipment. The gross weight of radio equipment aboard surface craft in the 1500 ton destroyer class is approximately 7100 pounds! Larger ships have correspondingly greater loads devoted to radio. Nevertheless, it is noteworthy that the radio load on patrol aircraft will represent between 1¼ per cent and 2¼ per cent of the fully loaded airplane weight, depending upon the size of the plane, in contrast to which less than one-quarter of 1 per cent is charged to radio in the above destroyer. Even in aircraft of the fighter types, the proportion of radio load to the gross weight will be 1.0 per cent or larger!

Let us now examine the influence of bulk and weight limitations on the design of aircraft radio equipment, their effect upon its performance, and some of the disadvantages at which the designers are placed. At this juncture it may be well to point out that in addition to the dead weight of inoperative radio equipment aboard aircraft, the power demands of the apparatus during flight operation result in a further equivalent drain upon the airplane primary power plant, its engine, and this demand must be subtracted from the power available for propulsion.

Antennas.

Similarly, the antennas and their supports necessary for the transmission and reception of radio signals, especially those of the weighted, trailing wire types, add not only to the aerodynamic drag but in modern, highly maneuverable combat aircraft may seriously interfere with the effective arcs of gunfire and the maneuverability of the airplane. A further hazard is presented by both trailing-wire and fixed antennas (which may be mounted below the fuselage) in the case of carrier-based aircraft owing to the possibility of fouling the arresting gear during landings. At any rate, the present necessity for increased air speeds and the attainment of higher altitudes (with consequent icing temperatures and low atmospheric pressures) has resulted in shorter antennas and smaller masts or other antenna structures. These constrictions seriously impair the performance of the radio gear and adversely affect its bulk and weight. At the same time, the flying range of the airplane is being extended with the result that since the antennas, which must perform the all-important functions of radiating or collecting the available radio-frequency energy, have been curtailed, the power output of the equipment or the range and choice of operating frequencies provided therein, or both, must be further increased with an attendant increase in bulk and weight, unless extended communications are to be sacrificed and the general utility of the equipment jeopardized. Thus, the antenna constitutes the effective electrical load for radio equipment, and its length and electrical characteristics usually form a bottleneck in the design of light-weight equipment. The antenna

problem on Naval aircraft is not appreciably different from that of new construction surface ships wherein antenna space is being seriously diminished in an effort to reduce top hamper and silhouette.

Practically all Naval aircraft possess both fixed and trailing-wire types of antennas, in addition to a direction-finding loop antenna and possibly other forms of fixed antennae for special purposes such as radio instrument (" blind ") landing, homing, etc. The weighted trailing-wire, which is reeled out through a suitable fairlead in the under side of the hull or fuselage, provides a good radiator of particular advantage at the lower frequencies, but is obviously unsuitable at high speeds, for operations requiring rapid maneuvering and formation flying, and at high altitudes where the process of reeling in the antenna becomes a matter of considerable physical fatigue despite the use of oxygen. Whipping of the trailing-wire, together with its tendency to take deep dives and excursions, often resulting in rupture, and its lengthening of the airplane's conducting path for electrical discharges between charged clouds, make this type even more objectionable if not dangerous. Accordingly this type of antenna, although generally available, has grown in disfavor, except perhaps for the larger seaplanes having long cruising radii where a fixed antenna must nevertheless be resorted to when the airplane is down on the water.

Fixed antennas assume various forms on Naval aircraft but the customary installations have consisted either of a fore-and-aft wire suspended between a stub mast, usually mounted on the upper side of the fuselage just aft of the engine, and the stabilizer or some other projecting part of the tail structure, with a lead-in brought into the fuselage from one end or other point of the horizontal wire; or a horizontal V-shaped arrangement strung from wing tips to tail with a lead-in from some point on the horizontal portion. On larger airplanes a combination of these arrangements may be employed. A typical installation on a modern fighter will consist of a 15 or 20-foot fore-and-aft antenna elevated between 3 and 5 feet above the fuselage and having a lead-in approximately eight feet in length extending from the vertical stabilizer to an entering insulator abaft the cockpit, as may be

observed in Figure 1. Most Naval aircraft larger than single-cockpit fighters have a rotatable direction-finder loop antenna (enclosed in a toroidal metal housing, split and insulated at a point on its circumference in order to avoid its short-circuiting effect on the inner loop) of approximately 12 inch O. D. in addition to one or more of the above types of antennas, and many aircraft may also carry a three or four-foot vertical mast antenna for use on ultra high frequencies (frequencies above 30 Megacycles), the mast being either retractable or collapsible if extending below the fuselage belly.

From the foregoing it may be appreciated that the antenna requirements for radio, despite the inherent limitation of reduced dimensions, incur a not inconsiderable aerodynamic drag and weight, especially when one considers the effect of ice accretion and the necessity for remotely controlled loop rotating mechanisms in many installations. The electrical effect of ice on the antenna is a detuning of the antenna circuit, and reduction in transmitted power or of received signal, caused by the large increase in dielectric constant of the ice surrounding the antenna over that of air. In the case of fixed wire antennas an attempt is made to reduce the ice load and render ice formation unstable under icing conditions by keeping the angle between the wire and the direction of the slip-stream less than about 20 degrees; nevertheless, an appreciable amount of ice may form under certain conditions, and exposed loop antennas offer a more difficult problem, notably in large seaplanes of the patrol types where the closed, all-metal hulls of such craft require mounting the loop external to the skin.

In Figure 2 the D. F. loop antenna on a representative patrol plane may be discerned immediately above the pilot's compartment and outlined against the port engine at the angle shown. The wing-to-tail fixed antennas may also be faintly distinguished in the photograph.

The wing-tip-to-tail type of antenna is a better radiator than the fore-and-aft antenna but it suffers from drag at high speeds, appreciable icing, and instability in the slip-stream. It is also a hazard to parachute descents in emergency, and is liable to be shot away by the guns, when it constitutes a further hazard should it become fouled with the tail surfaces. Practically all considerations except the electrical tend to favor the fore-and-aft antenna.

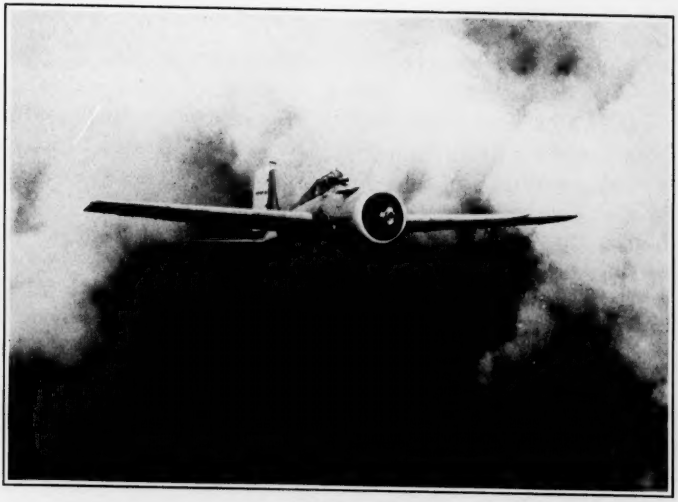


FIGURE 1.

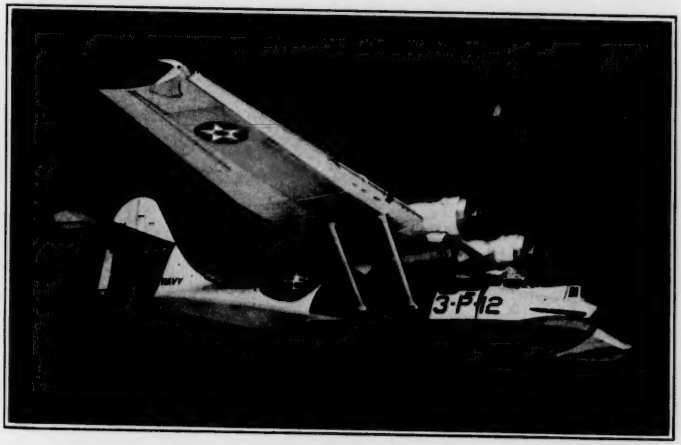


FIGURE 2.

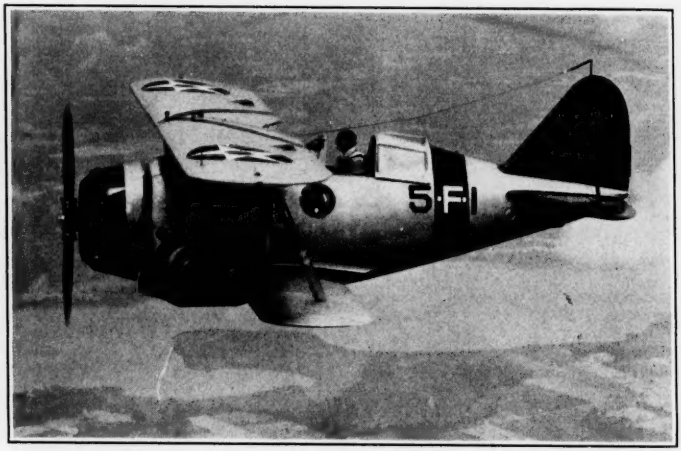


FIGURE 3.—NAVY FIGHTER PLANE OF AN OBSOLESCENT TYPE SHOWING A WING-TO-TAIL ANTENNA INSTALLATION.

Unfortunately, even here full advantage cannot be taken of its maximum possibilities since, in the case of fighters and other small aircraft of the monoplane type, the location of the antenna supporting mast forward of the cockpit and wings, as shown in Figure 1, adds substantially to the parasite drag of the airplane, with consequent reduction of speed at full throttle, which can be largely or entirely offset by locating the mast aft of the cockpit. This latter procedure results in an almost prohibitively short and ineffectual antenna, the handicap of which can only be partly overcome in the radio equipment, even at the sacrifice of increased weight therein. In this particular, an increase in weight probably can be afforded since it will not materially detract from the maximum speed, whereas the drag reduction contributes toward sustaining or promoting this speed. It is reported that twice the radiated output at the normal working frequencies is obtained with antennas having benefit of the present mast location, as illustrated in Figure 1, over that obtainable with the aerodynamically preferred mast location further aft, using the same radio equipment in each case. The relative effectiveness of the larger antenna is, within limits, increasingly greater as the operating frequency is lowered.

From the electrical standpoint, when antenna dimensions are shrunk the weight of the airplane's radio equipment must be increased in order not to penalize satisfactory communications, unless some compromise in service requirements is made. There are numerous reasons for this. The field strength at a distant receiving point may be conveniently thought of as being proportional to the radiation resistance of the transmitting antenna, or more accurately to the square-root of this equivalent resistance, at any assigned radio frequency. Thus, the power radiated is equal to $I_a^2 R_r$ where I_a is the antenna current and R_r is the radiation resistance of the antenna. The total antenna resistance is the sum of the radiation resistance and the loss resistance resulting from wire and "ground" resistance, corona, eddy currents induced in neighboring structures and conductors, and dielectric losses arising from imperfect dielectrics located in the field of the antenna, and this sum determines the amount of energy that must be supplied to the antenna to produce a given current. The efficiency of the antenna as a radiator (and, reciprocally, as a collector of radiated

energy) is the ratio of radiation to total resistance and this represents the fraction of the total energy supplied to the antenna which is converted into radio waves. As the overall dimensions of the antenna are decreased, the radiation resistance and efficiency are lowered accordingly. It should be recalled here that practically all aircraft antennas come under the "grounded vertical wire" category and terminate at the lower end in the airplane's metal structure which then becomes a somewhat distorted "ground plane" in the geometric sense. Also, vertical polarization of the space wave is generally more effective from the standpoint of all-around non-directional coverage and "effective height" whereas an antenna suitable to fulfill the requirements for horizontal polarization would be additionally undesirable from a structural and aerodynamic viewpoint. Under these conditions the radiation resistance is proportional to the square of the effective height of the antenna which in turn depends upon its physical size. Hence, it is important that the antenna possess as great a vertical component as possible in order that the intensity of the vertically polarized field will be as great as possible. A decrease of the vertical component of physical height may be somewhat compensated for by top loading; that is, by increasing the electrical capacitance at the upper end of the antenna which is accomplished by enlarging the horizontal portion of the antenna. This has the electrical effect of raising the current in the exposed vertical section of the antenna where it does the most good. Except on large aircraft, both the vertical and horizontal dimensions have been drastically reduced.

The horizontal length of the antenna contributes little else than capacitance at intermediate frequencies because when the antenna has a flat top the radiation from the flat top will be substantially zero unless the antenna height approaches or exceeds a quarter wave length. This results from the fact that with low heights the radiation from the flat top is almost completely neutralized by the radiation from its electrical image in the associated "ground plane" and which is in phase opposition.

Most fixed antennas excepting those for ultra-high-frequency operate below their fundamental or natural periods at frequencies below about 3000 Kilocycles (i.e., at frequencies lower than that

necessary to produce quarter-wave resonance in the antenna) and therefore require series inductance loading to neutralize the capacitive reactance of the antenna and ensure maximum antenna current. In small aircraft of the fighter types the equivalent antenna capacitance predominates and becomes larger with increasing frequency (requiring less series loading inductance) until a frequency in the neighborhood of 10 Megacycles is attained. Typical curves showing the measured equivalent capacitance and total resistance of an antenna installation similar to that shown in Figure 3 are illustrated in Figure 4 while Figure 5 shows representative values for a straight fore-and-aft antenna on a monoplane of the scout-fighter type.

In any case, at frequencies higher than that corresponding to the natural period the antenna exhibits inductive reactance, which must be neutralized by adding lumped capacitance in series with the antenna circuit in order to establish resonance, until a condition of half-wave resonance is obtained when the cycle reverses. The antenna characteristics thereafter conform more nearly to the case of a simple grounded wire and are reasonably predictable on the basis of total physical length, probably due to the increased electrical height of the antenna. This is illustrated by the curves shown in Figures 5 and 6, which are self-explanatory. It is evident that for antennas whose dimensions are short with respect to the operating frequency series loading inductance must be incorporated in the radio apparatus. Thus, the exposed portion of the antenna extending outside the fuselage may be thought of as useful load insofar as the actual radiation or reception of energy is concerned and the internal non-radiating part, which includes the lumped electrical loading, as parasitic, wasted load. Or again, the useful radiation is directly proportional to the meter-amperes when the effective height of the antenna is expressed in meters and the antenna current in amperes.

The losses associated with the loading inductance must be added to the loss resistance of the antenna itself. For a given radio frequency all these losses increase as the antenna size is diminished. The effect of increased losses and reduced antenna efficiency may be observed in Figures 7 and 8 which show sample calculations for typical fixed antennas at medium high frequencies. If the fre-

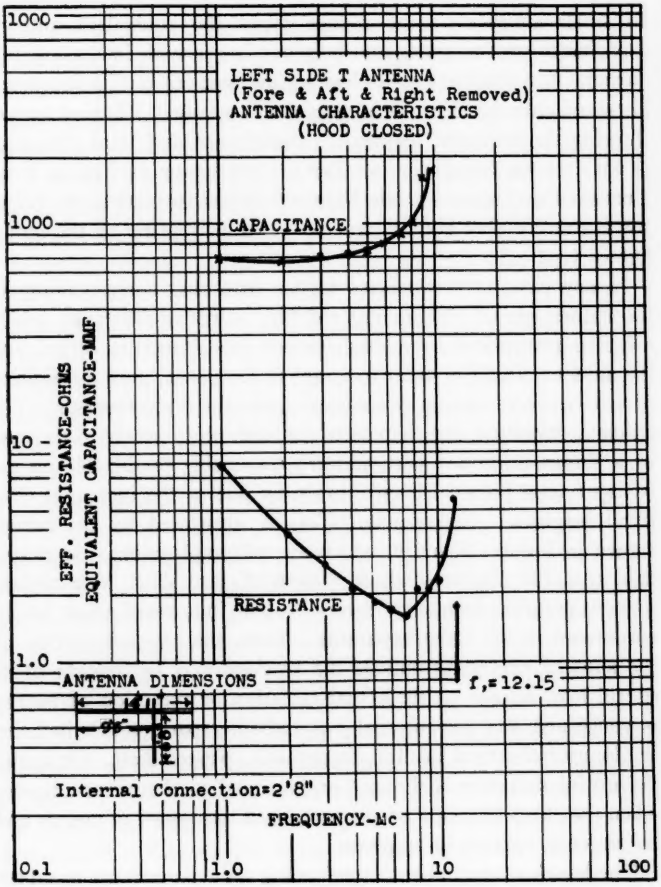

LEFT SIDE T ANTENNA
(Fore & Aft & Right Removed)
ANTENNA CHARACTERISTICS
(HOOD CLOSED)
1000
1000
CAPACITANCE
EFF. RESISTANCE-OHMS
EQUIVALENT CAPACITANCE-MMF
10
RESISTANCE
1.0
ANTENNA DIMENSIONS
f,=12.15
14'11"
9'5"
Internal Connection=2'8"
FREQUENCY-Mc
0.1
1.0
10
100

FIGURE 4.

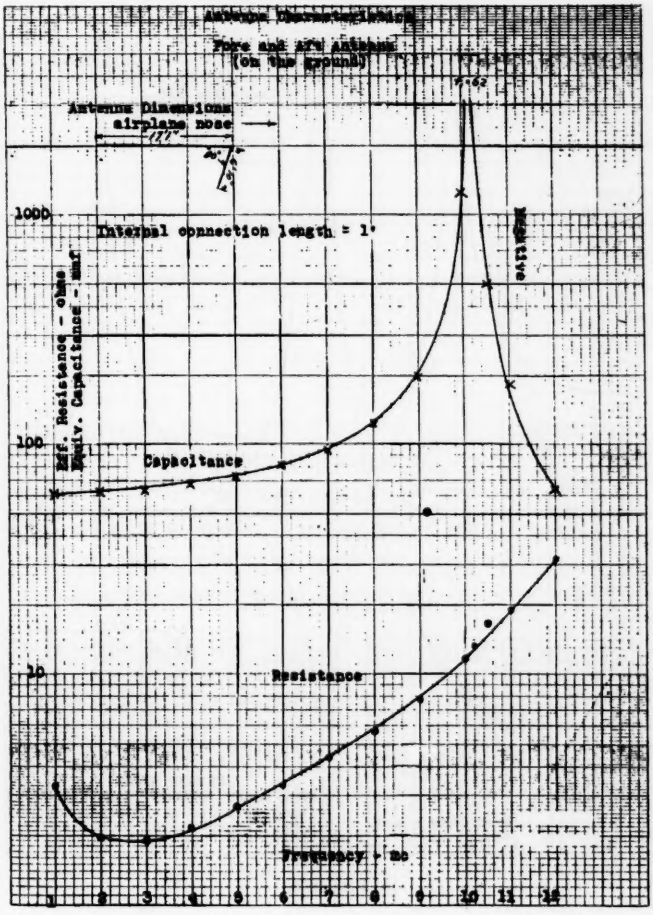

Antenna Characteristics
Fore and Aft Antenna
(On the ground)
Antenna Dimensions
airplane nose
1000
Internal connection length = 1'
Eff. Resistance - ohms
Equiv. Capacitance - mmf.
100
Capacitance
10
Resistance
Frequency - mc
1
2
3
4
5
6
7
8
9
10
11
12

FIGURE 5.

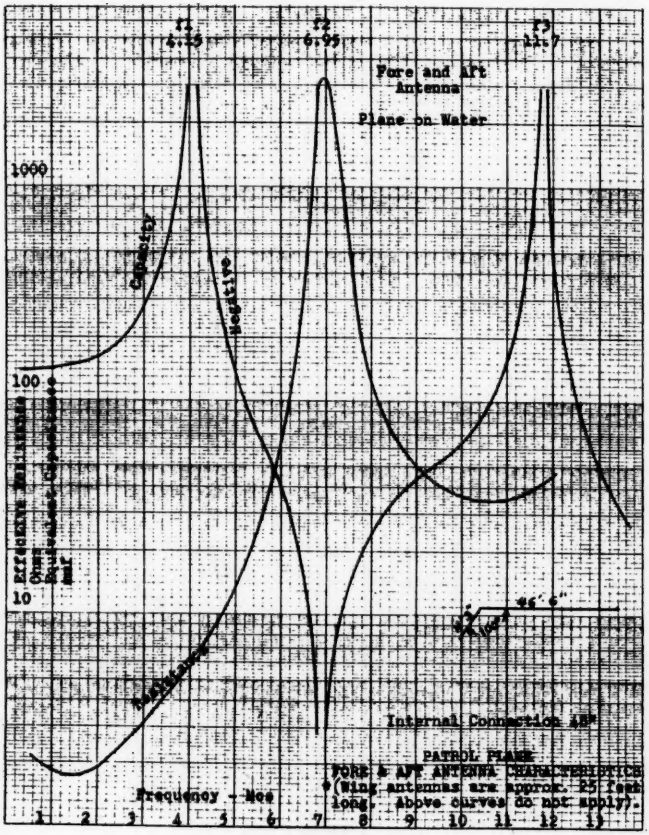

f1
4.15
f2
6.95
f3
11.7
Fore and Aft
Antenna
Plane on Water
1000
100
10
Capacity
Reactance
Resistance
Effective Antenna
Ohms
Reactance Component
Resistance Component
Internal Connection 45°
PATROL PLANE
FORE & AFT ANTENNA CHARACTERISTICS
(Wing antennas are approx. 25 feet
long. Above curves do not apply).
Frequency - Mcs
1 2 3 4 5 6 7 8 9 10 11 12 13

FIGURE 6.

FIXED ANTENNA
3000-10,000 KC.
17'6" FLAT TOP FORE & AFT L RESONANT FREQ. 9.25 MCS.

FREQUENCY	3000-5000 KC.	5000-7000 KC.	7000-10000 KC.
ANT. CAP. $\mu\mu fd.$	80 - 89	89 - 125	106 - INF.
ANT. RES.- OHMS.	2.2 - 2.3	2.3 - 3.6	2.7 - 10
ANT. REAC. X_{La} - OHMS	663 - 394	397 - 188	250 - 0
ANT. LOAD L - μ HEN.	35.2 - 13.8	14.0 - 4.40	6.63 - 0
ANT. LOAD R_{La} - OHMS	5.0 - 4.0	4.0 - 2.5	3.0 - 0
ANT. CURRENT I_a	3.32 - 3.28	3.59 - 3.46	3.80 - 2.26
ANT. VOLTS RMS $I_a X_{La}$ C W	2200-1290	1430 - 650	950 - 28
ANT. POWER $I_a R_{La}$ WATTS	24.2 - 24.5	29.6 - 43.2	38.9 - 76.1
ANT. LOADING LOSS (APPROX.)	60.8 - 60.5	55.4 - 41.8	46.1 - 8.9

FIGURE 7.

FIXED ANTENNA
3000-10,000 KC.
A = 20'4" FLAT TOP "T" TYPE RESONANT FREQ. 11.0 MCS.
B = 14'6" PER LEG "V" TYPE RESONANT FREQ. 7.7 MCS.

FREQUENCY - KCS.	3000	3000	5000	5000	6000	6000	9000	9000
LENGTH - FEET	A	B	A	B	A	B	A	B
C ANT. $\mu\mu fd.$	70	116	80	166	87	220	130	
R ANT. - OHMS.	1.7	1.26	2.2	1.4	2.9	1.7	12	3
L ANT. LOAD - μ HEN.	40	24.5	13	6.2	8	3.2	2.5	CAP.
X_{La} - OHMS	752	460	406	195	300	121	141	
R_{La} - OHMS	5	3	2.7	1.3	2	0.8	0.94	
$R_a + R_{La}$	6.7	4.26	4.9	2.7	4.9	2.5	12.9	
I_a FOR 55 WATT TUBE C W OUTPUT	2.86	3.59	3.35	4.5	3.35	4.7	2.06	
$I_a^2 R_a$ ANT. - WATTS	14	16.2	24.6	28	32.5	37.5	51	
$I_a R_{La}$ ANT. LOSS - WATTS	41	39	30.4	27	22.5	17.5	4	
$I_a X_{La}$ R M S VOLTS C W	2160	1650	1360					
$I_a X_{La}$ R M S VOLTS PHONE AT PEAK OF 75% MODULATION 35 WATT CARRIER.	2760		1740					

FIGURE 8.

quency be considered as constant each table applies conversely to variation of the antenna dimensions and parameters which electrically then become effectively larger as the frequency is raised. If the radio transmitting apparatus is to compensate for the reduced radiation efficiency of the antenna and the greater proportion of loss resistance to useful radiation resistance, either the amount of energy dissipated in losses must be reduced thus allowing a larger proportion of the available energy to be devoted to useful radiation or the total power output obtainable from the transmitter must be increased. Either or both of these conditions can be satisfied, if weight and bulk be permitted to increase. Fortunately the tendency toward increased weight has been partly though not completely counterbalanced by advancements and new developments in design.

We shall next examine in some detail the many factors contributing to weight in the apparatus itself, including the relations between bulk and weight, and the numerous methods and devices by which weight-saving is achieved.

SUPERCHARGING OF DIESEL ENGINES.

By Edward D. Newell,* Member.

The author classifies and describes the various methods which have been applied to supercharging Diesel engines, and presents examples of each.

Supercharging, as applied to internal combustion engines, is the process of supplying air for combustion at a pressure greater than that attained by natural or atmospheric induction. The purpose of supercharging is to increase the output of an engine, the combustion of a greater quantity of fuel per cycle being made possible by the greater charge of air. Although patents on certain supercharging methods were granted as early as the beginning of the present century, it was not until World War I that their development commenced in earnest in this country, at which time the necessity for supercharging gasoline engines for aircraft use became apparent. These early efforts met with considerable success and no doubt paved the way for recognition of supercharging as a commercially feasible development when applied to Diesel engines.

The first types of superchargers to receive attention were the exhaust turbo-charger [1] and the gear driven rotary blower. The former consisted of a gas turbine on the extended shaft of a centrifugal blower and derived its energy from the exhaust gases of the engine. The second type, the rotary blower, was mechanically driven from the engine by means of a light, high speed gear train. Both types were designed to maintain sea level pressure in the induction manifold at various altitudes and thereby maintain substantially sea level output. Since its early development in the field of aviation, supercharging has found useful application to many installations of diversified nature, such as racing boats and

* Diesel Engine Section, Design Division, Bureau of Ships.

automobiles, Diesel locomotives, Diesel cargo, passenger and naval vessels, power plants for peak load conditions and, in recent years to a limited extent, for gasoline engined passenger automobiles.

When applied to the Diesel engine, supercharging permits the output of a given engine to be increased on the order of 20-50 per cent *without involving additional thermal or mechanical loads of appreciable magnitudes.* This has enabled manufacturers of 4-cycle engines in Europe and the United States to actively compete with the 2-cycle field. More than two years ago a prominent British journal [2] made the following prophesy, "The time will probably come when no four-stroke engine of moderate or high power is constructed unless fitted for pressure-charging." A few months ago, the same journal [3] stated, "The majority of the leading manufacturers of four-stroke stationary engines in this country (England) build them as standardized units with supercharging." This shows that supercharging is utilized extensively in Europe even though it is used only on a small scale as yet in the United States. No attempt will be made in this discussion to compare the merits of 4-cycle supercharged engines with the 2-cycle type, except to say that, whereas the latter has the advantage on the basis of space and weight, the 4-cycle engine possesses inherent qualities recognized as conducive to low maintenance, so that where a small amount of excess weight and size is of no consequence, the installation of a supercharged 4-cycle engine may be readily justified.

In Table I are listed the various types of superchargers for Diesel engines and representative installations of each type. Table II includes general data on the characteristics and performance of a number of Diesel engines for both the supercharged and unsupercharged condition.

Electric motor-driven superchargers (Type (1), Table I), are employed in the propelling plants of several seagoing vessels of foreign registry, whereas in this country a notable installation is that of a large pipe line dredge owned and operated by Shell Producers Company of Tampa, Florida. The two engines installed are of the same bore and stroke, one having eight cylinders and the other six, and were manufactured by the National Supply Company, Springfield, Ohio. The author was employed by the

TABLE I.

Group	Sub-Group	Type	Manufacturer
I Supercharging at expense of Engine Output	(A) Full-Stroke	(1) Electric Motor Driven	Elliott Co.
		(2) Gear Driven from Engine	Krupp
		(3) Belt Driven from Engine	McCulloch
		(4) Air Compressed on Lower Side of Piston	(a) Electric Boat Co. (b) Werkspoor
		(5) Throttled Exhaust Valve	Junkers
		(6) Chain Driven from Engine	Burmeister & Wain
	(B) After-charging	(7) Auxiliary Compressor on Scavenging Piston	Sulzer
		(8) Compound-Admission	Sulzer
II Supercharging by Exhaust Gas Turbo-Blower		(9) Rateau	(a) Elliott Co.
		(10) Buchi	(b) Brown, Boveri
		(11) Lorenzen [20]	
III Supercharging by Dynamic Fluid Action		(12) WIBU	Wicinski & Bujak
		(13) Kadenacy	Petters, Ltd.

buyer to inspect and test these engines at the plant of the manufacturer, and part of the test data is shown in Table II, line 1. Figure 1 is an illustration of the 6-cylinder engine set up on the test stand with blower attached. The blower was manufactured by The Elliott Company, is of the centrifugal type, and has a rated capacity of 3000 c.f.m. Referring to Table I, the output of this engine was increased by 27.6 per cent without exceeding the maximum exhaust temperature of 725 degrees F. set as the limit for the unsupercharged engine. In fact, the net output was increased to 1040 BHP., a 45 per cent increase over the unsupercharged operation, by a reduction in exhaust manifold pressure from 3.8 to 0.7 inches Hg., and even under these conditions the exhaust

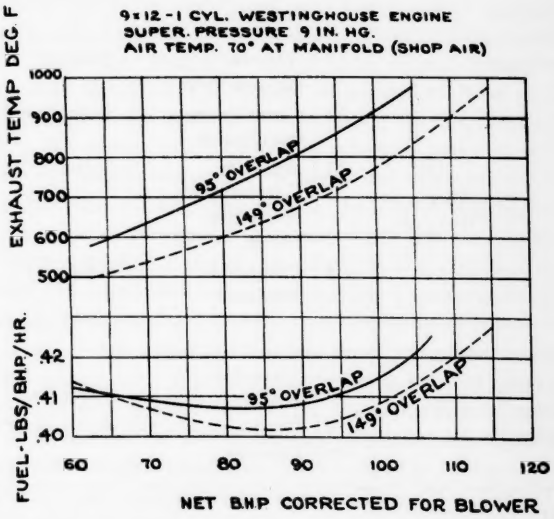


FIGURE 2.—EFFECT OF VALVE OVERLAP ON FUEL CONSUMPTION AND EXHAUST TEMPERATURE.

temperature was only 727 degrees F. Since the excessive exhaust pressure was due to an undersized muffler, it is reasonable to assume that appreciable gains over those shown in Table I could be realized by employing an exhaust system of less resistance. To accomplish these power gains, no design changes of fundamental

TABL

Line No.	Engine Manufacturer	Cycle	No. Cyls.	Bore Ins.	Stroke Ins.	BHP (Net)		RPM.	
						Unsupercharged	Supercharged	Unsupercharged	Su cha
1	National Supply Co.	4	6	14½	20	715	913	360	36
2	Krupp	4	6	17.72	30.7	670	930	148.5	16
3	National Supply Co.	4	6	4½	5¾	128	200	2200	22
4	Electric Boat Co.	4	6	14	14½		867		4
5	M. A. N.	4	8	25.6	55.2	2575	3500	110.0	12
6	Sulzer	2	4	23.6	33.1	1500	1800	150	1
7	Burmeister & Wain	4	8	29.2	59.0	3300	4300	101	1
8	M. A. N.	4	6	11.8	14.97	700	950	700	7
9	American Locomotive Co.	4	6	12½	13	600	900	700	7
10	Cooper-Bessemer Corp.	4	8	8	10½	400	600	900	9
11	Enterprise Engine Co.	4	6	12	15	650	1000	650	6
12		4	1	11.8	17.7	60	75	300	3
13	Petters, Ltd.	2	2	8½	13	125	172	500	5

* Based on gross output (includes power to drive blower).

TABLE II

RPM.		Piston Speed Feet/Min.		BMEP, Lbs./Sq. In.		Increase in BMEP %	Method of Supercharging	Typical Installation
nsuper-harged	Super-charged	Unsuper-charged	Super-charged	Unsuper-charged	Super-charged			
360	360	1200	1200	79.3	112.8*	42.2	Motor Driven Centrifugal	Pipe Line Dredge
148.5	165	760	850	79.0	100.0	26.6	Gear Driven	Cargo Ship *Werner Vinnen* [35]
200	2200	2110	2110	84.0	131.6	56.7	Belt Driven from Engine	U. S. Naval Vessel
	460		1110		111.5		Under Piston	U. S. Naval Vessel
110.0	121.5	1012	1120	81.7	100.5	23.0	Under Piston	Anglo-Saxon Petroleum Co. Tankers [36]
150	150	827	827	68.2	81.6	20.0	After-Charging	Experimental [37]
101	110	982	1082	82.3	98.4	20.0	Exhaust Gas—Rateau	Passenger Ship *Agamemnon* [38]
700	700	1750	1750	80.6	109.5	35.7	Exhaust Gas—Rateau	French National Railways [39]
700	700	1520	1520	71.0	106.0	50.0	Exhaust Gas—Buchi	Switching Locomotive
900	900	1575	1575	84.0	125.0	50.0	Exhaust Gas—Buchi	Yacht *Trouper*
650	650	1625	1625	77.7	119.8	54.0	Exhaust Gas—Buchi	Tug *Keith*
300	300	885	885	81.5	102.0	25	WIBU	Experimental [40]
500	500	1083	1083	67.1	93.0	38.8	Kadenacy [34]	Experimental

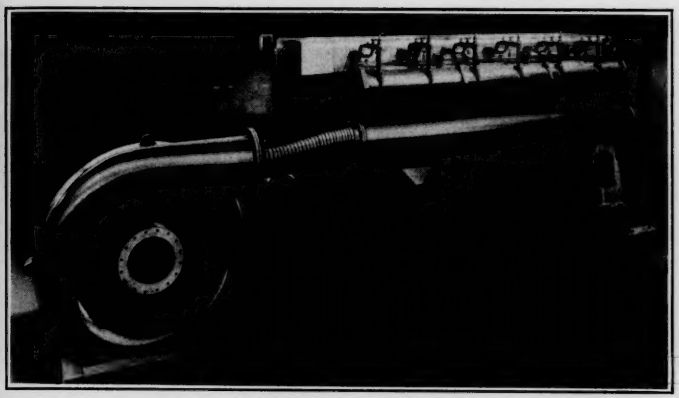


FIGURE 1.—NATIONAL SUPPLY CO. 6-CYLINDER ENGINE AND BLOWER.

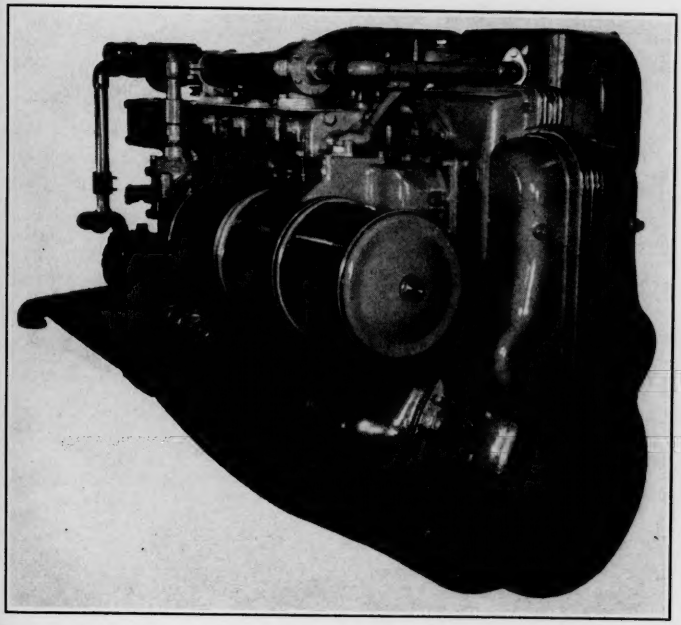


FIGURE 4.—NATIONAL SUPPLY CO. HIGH SPEED MARINE ENGINE.

FIGURE 5.—McCULLOCH SUPERCHARGER ASSEMBLY.

FIGURE 6.—McCULLOCH SUPERCHARGER WITH END PLATE REMOVED.

nature were made except to provide a special camshaft for obtaining the overlap of the exhaust and inlet valves necessary for the proper scavenging and cooling of the combustion space. This overlap usually is between 140 and 150 degrees of the crank angle. Figure 2 is taken from a comprehensive article on the effects of supercharging by Mr. Russell Pyles,[4] and shows the importance of valve overlap on exhaust temperature and fuel consumption since considerable advantage was realized in both by an increase in overlap from 95 to 149 degrees.

In order that the maximum combustion pressure in the supercharged engine would not exceed the 850 pounds maximum for which the unsupercharged engine was designed, the compression ratio was decreased; the super-atmospheric intake manifold pressure due to supercharging then brought the compression pressure up to the unsupercharged value. The increased output was thus obtained without increase in exhaust temperature or maximum cylinder pressure. Since the size of connecting rod and main bearings is largely based upon maximum cylinder pressure, no change in design of these parts is necessary when supercharging even though the mean pressure is increased considerably. Despite the lower compression pressures, the National Supply Company engines mentioned above started readily with the blowers idle and the induction manifolds under atmospheric pressure.

Direct drive marine installations employing motor driven superchargers usually have the speed of the motor controlled by the engine governor for varying the blower output with changing engine speed and load. While it is true that the motor driven blower absorbs a portion of the useful engine output, the simplicity and dependability of such a system is undeniable.

A direct driven supercharger (Type (2), Table I) is frequently driven by means of a gear train. As in the case of the motor driven type, it also reduces the useful output of the engine. Such superchargers have found application for direct drive marine Diesel propelling engines where the output of the engine varies with the speed. The supercharger is usually of the displacement type so that its output is proportional to its speed and the degree of supercharging of the engine is thus maintained automatically. Figure 3 shows a 6-cylinder, 4-cycle, 930 BHP. Krupp engine

FIGURE 5.—McCULLOCH SUPERCHARGER ASSEMBLY.

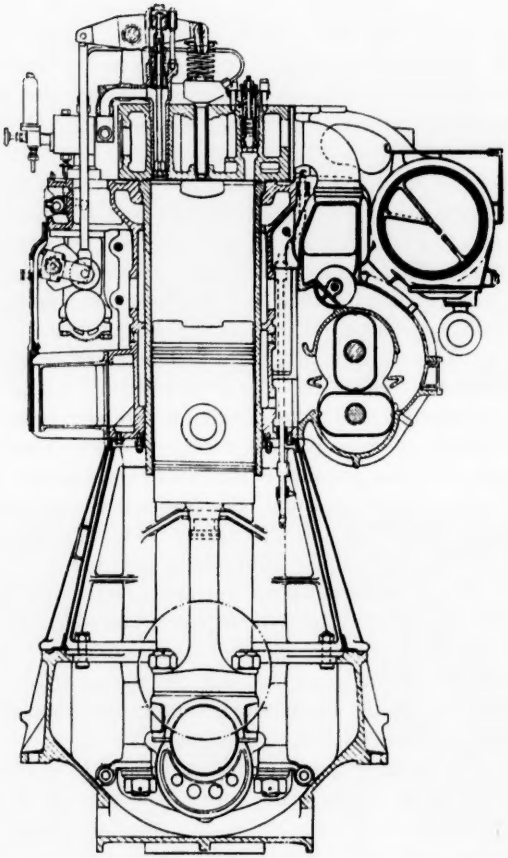


FIGURE 3.—6-CYLINDER KRUPP ENGINE WITH GEAR-DRIVEN BLOWER.

with supercharger, as installed on the cargo ship *Werner Vinnen*. Line 2 of Table II shows that the supercharger increased the BMEP. of this engine by approximately 27 per cent.

Type (3) of Table I covers superchargers which are belt driven from the engine. An example of this type is manufactured by the National Supply Company's Philadelphia plant and is shown in line 3, Table II. This engine is noteworthy in that it is one of the first of the automotive type to be supercharged in the United States. Figure 4 is an illustration of this engine. In Figure 5 is seen the blower itself, which is of the McCulloch positive displacement type. Figure 6 illustrates the blower with end plate removed, showing the 3-lobed rotors which are straight. However, the housing contains helical ports which are claimed to effect quiet operation and uniform delivery.

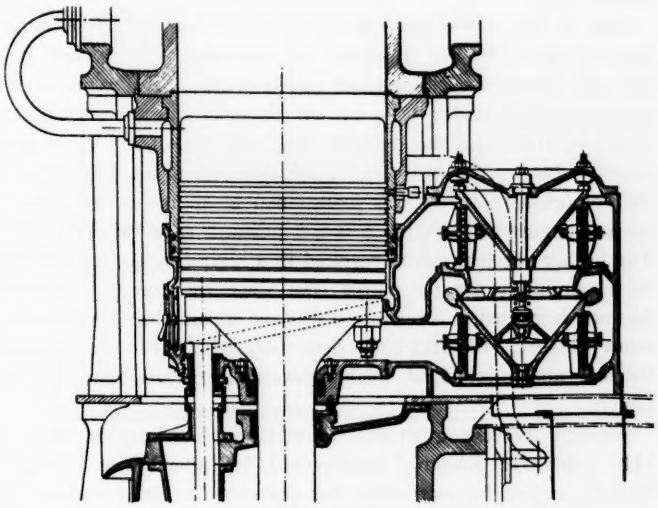


FIGURE 7.—WERKSPOOR "UNDER PISTON" SUPERCHARGER.

Figure 7 illustrates the principle of operation of the "Werkspoor" type of supercharging, Type (4) of Table I. The space under the power piston is arranged for use as a compressor with automatic inlet and discharge valves. Air is compressed to 4-5

pounds gage and introduced into the working cylinders in the usual manner. This being a 4-cycle engine, ample air for scavenging and supercharging is available, since two strokes of the compressor occur during each working cycle. This type of supercharging is limited to single acting engines of the crosshead type. The simplicity of such a system, together with its low first cost and its low requirements for space and weight, are its chief advantages. This system is employed by the Werkspoor and M. A. N. companies in Europe and by the Electric Boat Company in this country. Data on the latter's engine are shown in Table II, line 4. Both Werkspoor and M. A. N. engines using this system of supercharging were installed on a number of the Anglo-Saxon Petroleum Company's tankers. Line 5 of Table II indicates that by supercharging, the output of the M. A. N. engines was increased 36 per cent.

One of the earliest methods of supercharging the Diesel engine was attempted by Dr. Junkers,[5] of Germany, who applied it to his well known 2-cycle opposed piston engine. Reference to this system is made under Type (5) in Table I. Supercharging consisted of throttling the exhaust near the end of the scavenging period whereby the pressure in the cylinder at the beginning of the compression stroke was maintained at approximately that of the scavenging air. Figure 8 is the indicator card for this engine. The higher initial pressure resulted in a higher mean pressure and correspondingly greater output, but since the compression ratio was not decreased, this operation was accompanied by higher maximum pressure. Inability to produce material equal to the increased thermal and mechanical loads prevented the adoption of this system.

Another interesting attempt occurred in Germany as early as 1916 when Dr. Rheims[6] endeavored to supercharge a 2-cycle M.A.N. engine by increasing the quantity of fuel injection air. This method resulted in an increase in fuel consumption and, therefore, was uneconomical.

In addition to the supercharging systems already mentioned, another method, also operated at the expense of engine output and known as "after-charging" or "topping up," is employed on both 4- and 2-cycle engines. The term "after-charging" is de-

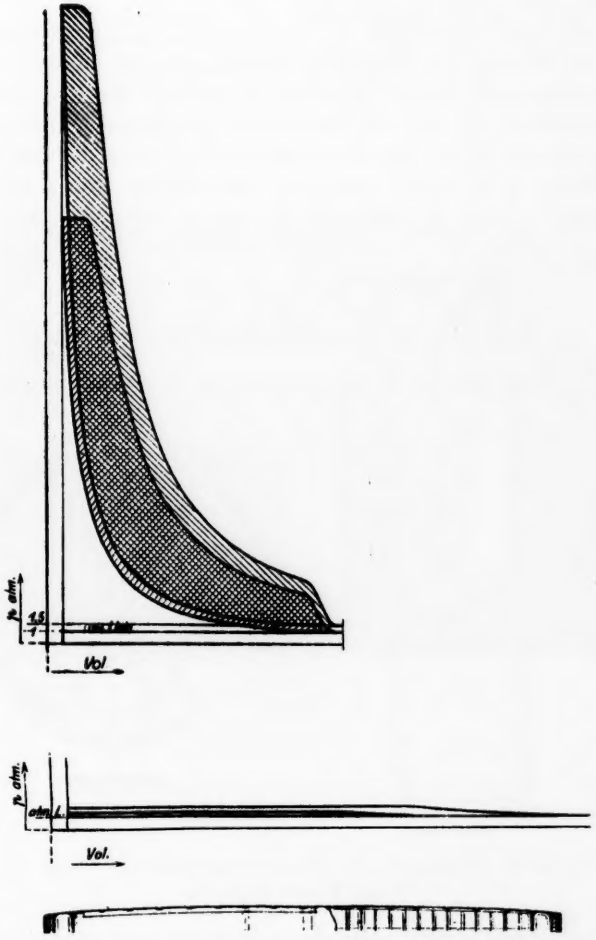


FIGURE 8.—INDICATOR CARD FOR JUNKERS OPPOSED PISTON ENGINE SHOWING SUPERCHARGED AND UNSUPERCHARGED CONDITION.

rived from the fact the supercharging occurs after the normal induction process is completed.

Burmeister and Wain use a rotary type blower, chain-driven from the engine, to furnish the supercharging air for their after-charging system, Type (6), Table I. Figure 9 illustrates such an installation. In this case two positive displacement, rotary type blowers are driven from the crankshaft, have separate intake pipes (shown in the vertical position), and discharge into a common header. Figure 10 illustrates the type of valve used with this

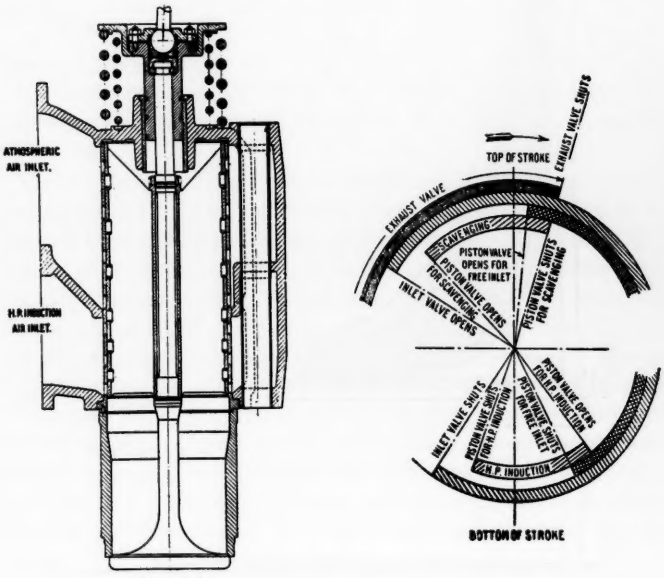


FIGURE 10.—BURMEISTER AND WAIN "AFTERCHARGING" VALVE AND VALVE TIMING DIAGRAM.

after-charging system. Also shown is the inlet and exhaust valve timing diagram. Scavenging is accomplished by means of high pressure air at the top of the stroke during approximately 70 degrees of the crank angle. Ports of the piston valve are open to the atmosphere for about 135 degrees, allowing natural aspiration

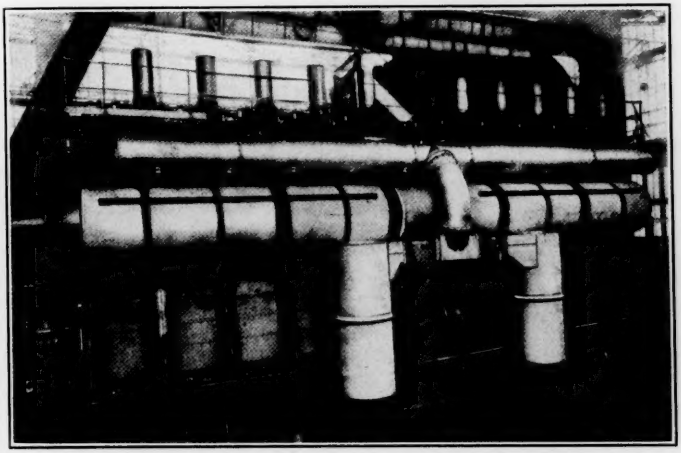


FIGURE 9.—BURMEISTER AND WAIN SUPERCHARGED ENGINE INSTALLED IN M.S. "VENUS".

during this period, and, for approximately 60 degrees crank angle at the bottom of the stroke, high pressure air for supercharging is admitted to the cylinder. Under these circumstances the blower has to supply only 60 per cent of the cylinder volume, whereas the amount required for full-stroke pressure induction is of the order of 130 per cent of the cylinder volume.[7] The example shown in Figure 9 is that of a B. & W. 4-cycle engine installed on the *Venus,* a 5000 H.P. passenger ship.

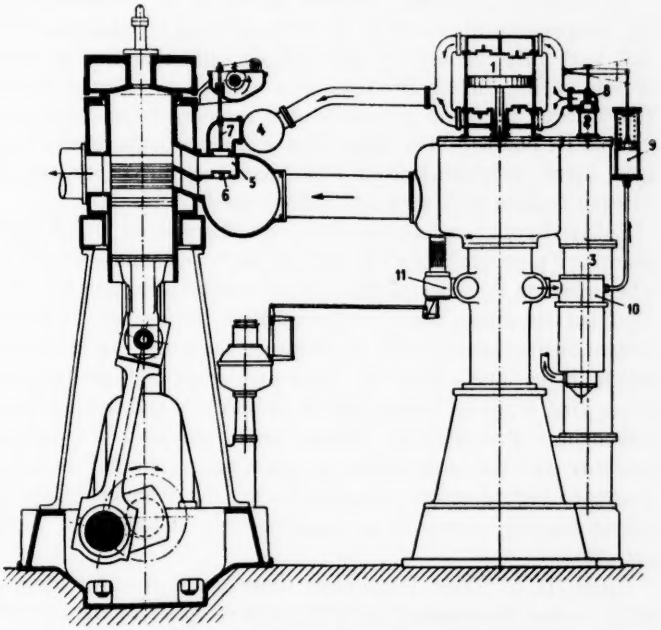


FIGURE 11.—DIAGRAMMATIC ARRANGEMENT OF SULZER SUPERCHARGED 2-CYCLE ENGINE.

Sulzer Brothers, of Winterthur, Switzerland, have adapted the after-charging principle to their 2-cycle engine Type 7, Table I. Figure 11 illustrates the arrangement, showing the supercharging compressor, 1, above the scavenging piston, discharging into the header, 4. As the power piston on the expansion stroke uncovers

the exhaust ports, air at 3 pounds gage flows from the scavenging header into the cylinder through the automatic valve, 6. As the piston proceeds to uncover the lower scavenging ports, scavenging air continues to flow through the ports until they are closed on the return stroke of the piston. At this instant the cam-operated valve 7, opens and allows supercharging air at 11.5 gage to fill the cylinder. Flow of the high pressure supercharging air continues until the upper ports are closed by the piston. A throttling device, actuated by the governor, controls the output of the supercharging compressor, which serves to effect a saving at loads less than full load. By the use of this type of after-charging on their 2-cycle engine, Sulzer Brothers were enabled to effect a 20 per cent increase in output as compared to standard 2-cycle operation (Table II, line 6). The data given are for an experimental engine, based on which this firm has made several conversions of existing engines with very satisfactory results.

Sulzer 4-cycle engines are also supercharged on the "after-charging" principle, known in this case as "compound-admission." The induction system resembles the conventional 4-cycle type except that air intake ports are provided in the cylinder near the bottom of the piston travel. In operation the power stroke is normal until the intake ports are uncovered, when high pressure air is supplied from an engine driven compressor and accomplishes scavenging. Following the exhaust stroke, atmospheric induction proceeds until the intake ports are again uncovered and the same source of high pressure air supercharges the cylinder. Gain in output for this system of pressure-charging is limited to 20-25 per cent.

Group II of Table I embraces those types of superchargers which derive their energy from the exhaust gases of the engines they serve. These types are limited to 4-cycle engines. Three different designs of this type, namely, Rateau, Buchi, and Lorenzen, have been used; they differ somewhat in details of design, but are basically alike and will be treated accordingly. The exhaust gas turbo-blower used in pressure-charging of Diesel engines is essentially the same as the airplane supercharger described above and consists of an exhaust gas turbine on the same shaft with a centrifugal blower. In some installations [8] coolers were placed in

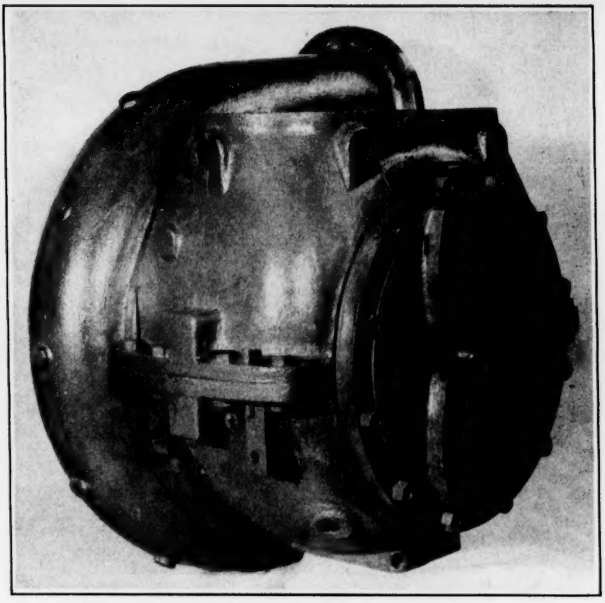
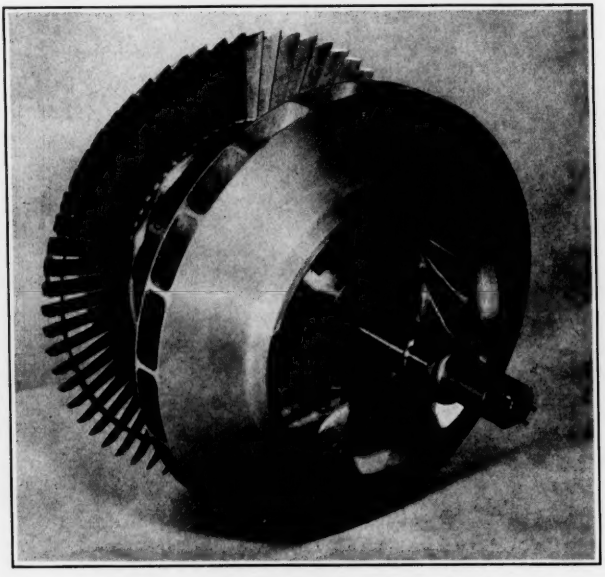


FIGURE 12A.—BUCHI TURBO-CHARGER ASSEMBLY
(ELLIOTT CO. MANUFACTURE).



12B.—BUCHI TURBO-CHARGER ROTOR ASSEMBLY
(ELLIOTT CO. MANUFACTURE).

the discharge of the blower for the purpose of lowering the temperature of the charging air and thereby increasing its specific weight. To adapt a normal 4-cycle Diesel engine to the use of the turbo-charger, alterations to the valve mechanism, as stated earlier, are usually necessary to allow the intake and exhaust valves of a particular cylinder to be open simultaneously during a portion of the induction stroke, thereby effecting scavenging of the cylinder and cooling of its related parts. For this purpose approximately 20 per cent of the total charging air delivered by the blower is allowed to flow through the cylinder before the exhaust valve closes. In order that exhausting cylinders may not interfere with the cylinders undergoing scavenging, not more than three cylinders are allowed to exhaust into the same manifold, the exhaust headers being arranged to suit the firing sequence of the particular engine. In the development of the Buchi system it was found[9] that a pressure ahead of the turbine approximately equal to that of the blower discharge was necessary in order for the turbine to develop sufficient power. This meant that charging air entering the cylinder and exhaust gases in the manifold of that cylinder would be at virtually the same pressure. To effect an appreciable pressure differential between the induction and exhaust manifolds for efficient scavenging, advantage is taken of the pressure oscillations in the exhaust pipe. These oscillations are accentuated by the proper design of the exhaust manifolds and the turbine inlets. Early in the exhaust stroke, the surge of the exhaust gases creates a high pressure wave in the restricted manifold with resultant high kinetic energy of the gases conducive to good operation of the turbine. This initial surge is followed by a low pressure wave. At this instant the intake valve is opened, and, due to the pressure differential caused by the low pressure wave in the exhaust manifold, air flows through the cylinder, thereby accomplishing scavenging and cooling. The effect of the cooling air is important from the standpoint of the turbine as well as the engine, since at present the maximum temperature which the materials involved will satisfactorily withstand is about 1100 degrees F.[10] Figure 12a illustrates a Buchi turbo-charging unit as manufactured by The Elliott Company. Figure 12b shows the turbine and blower rotor assembly of the same unit.

Figure 13 is an interesting plot representing engine and turbo-blower conditions on a Ruston 1000 HP., 6-cylinder, 15 × 20, 375 RPM. stationary engine driving a generator.[11] Referring to the graph, it is seen the fuel consumption averages slightly over 0.37 pounds per BHP.-Hr. for a range of BMEP. of 50-120 pounds per square inch, or 50-120 per cent load. At rated load of 100 BMEP., the blower discharge pressure is roughly 3 pounds, whereas the average exhaust pressure ahead of the turbine is about 2.5 pounds. In the majority of Buchi installations, however, the blower discharge pressure is between 4 and 5 pounds. For

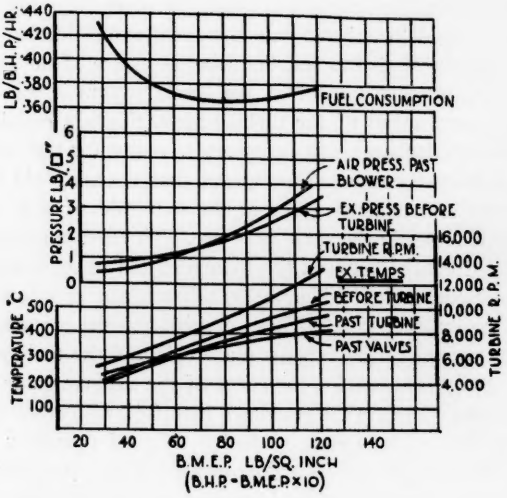


FIGURE 13.—PERFORMANCE DATA ON A RUSTON ENGINE WITH BUCHI SUPERCHARGER.

the same conditions, the exhaust temperature just past the valves is 390 degrees C. (735 degrees F.), and is 475 degrees C. (887 degrees F.) and 420 degrees C. (788 degrees F.), respectively, before and after the turbine. The rise in temperature between the exhaust valves and the turbine inlet is due to adiabatic expansion.

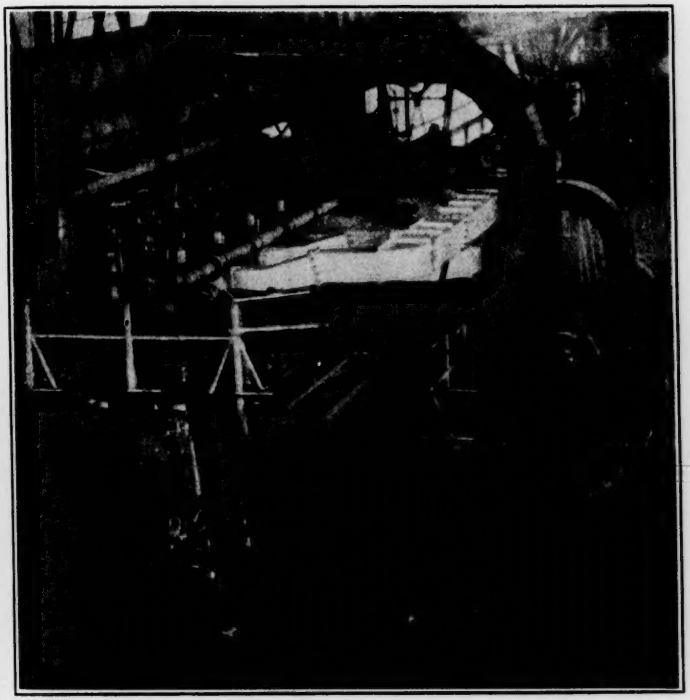


FIGURE 14.—BURMEISTER AND WAIN ENGINE WITH RATEAU SUPERCHARGER AS INSTALLED ON M.S. "AGAMEMNON".

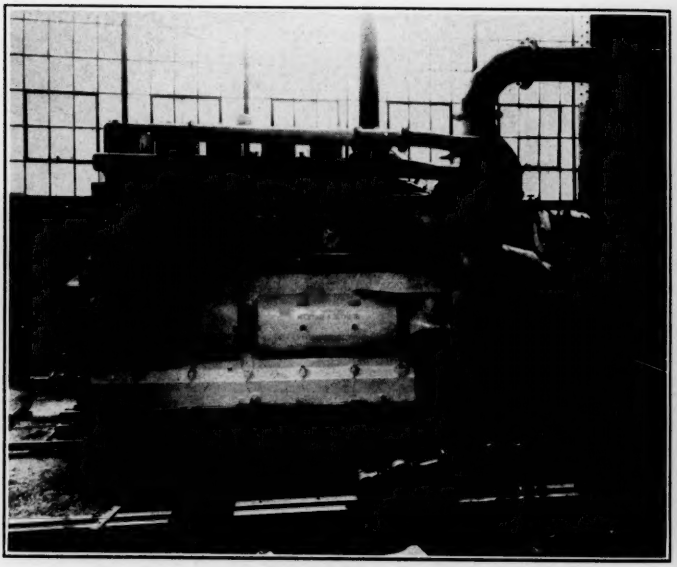


FIGURE 15.—AMERICAN LOCOMOTIVE CO. ENGINE-GENERATOR WITH BUCHI SUPERCHARGER.

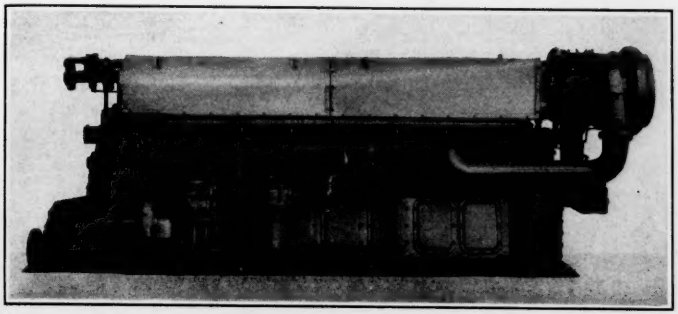


FIGURE 16A.—COOPER-BESSEMER SUPERCHARGED ENGINE—SIDE VIEW.

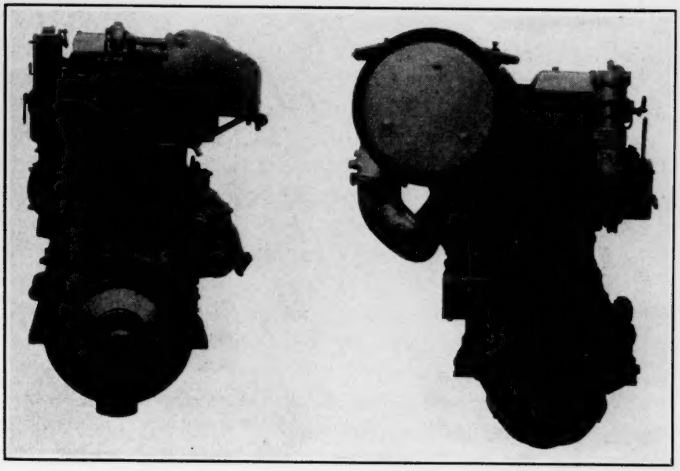


FIGURE 16B.—COOPER-BESSEMER SUPERCHARGED ENGINE—END VIEWS.

Supercharging by means of the exhaust turbo-blower has the advantage of quick response to load and speed variations. Whether the engine load, or its speed, or both vary, the energy of its exhaust gases undergoes a corresponding variation which in turn causes a change of supercharger output to meet the new conditions of operation. According to actual test [12] engines supercharged on the Buchi system show a slight improvement in fuel consumption over operation without supercharging, accompanied by lower exhaust temperatures.

Figure 14 illustrates the installation of a Rateau supercharger on an 8-cylinder, 4-cycle, B. & W. Marine engine. Line 7 of Table II shows that an increase in output of 30 per cent was realized by supercharging of this engine. Information on a M. A. N. engine, also supercharged by a Rateau unit, is given in Table II, line 8, a gain of almost 36 per cent being made.

Figure 15 shows a 6-cylinder, 4-cycle, 900 BHP. American Locomotive Company engine fitted with a Buchi supercharger. The first engine was installed in a Birmingham Southern Railroad transfer locomotive, and, from line 9, Table II, it can be seen that the output of the engine was improved 50 per cent by means of supercharging. Referring to Figure 15, the supercharging unit is shown mounted above the generator, forming a compact installation of roughly the same overall dimensions as the unsupercharged engine and generator unit. The American Locomotive Company was the first Diesel engine manufacturer in the United States to employ the Buchi system of supercharging and in the last four years has sold over 100 such units for locomotive service. Until recently this company was the only firm in this country with the rights to manufacture the Buchi supercharger, but the Elliott Company is now engaged in its manufacture.

The Cooper-Bessemer Corporation has converted some of their standard Diesel engines to supercharging, using the Buchi system. One outstanding installation was made on the yacht *Trouper,* owned by Mr. C. A. Tilt, President of the Diamond T Motor Car Company. Referring to line 10, Table II, the engine is rated at 600 BHP. at 900 RPM. supercharged, and 400 BHP. at the same speed unsupercharged—a gain of 50 per cent. Figure 16 is an illustration of this engine showing the Buchi unit mounted on the

engine. The blower discharge can be seen leading to the intake manifold. The hood, extending the length of the engine, covers the exhaust manifold consisting of four pipes, each of which serves two cylinders.

The General Motors Corporation, Cleveland Diesel Engine Division, has adapted their 16-cylinder, V-type engine to supercharging on the Buchi principle.

The Enterprise Engine Corporation, San Francisco, is another manufacturer applying the Buchi system to their standard line of engines. Referring to the data in Table II, line 11, this engine is rated at 650 BHP. atmospheric and 1000 supercharged, an increase of 54 per cent. Two engines of this type were installed in a western river tug, the *Keith*.

Advocates of the Buchi system claim [13] an increase in continuous output of 50 per cent is possible, whereas the cost of the engine is increased only 10 per cent and the fuel economy improved 5 per cent.

The third and last group in Table I comprises those types of superchargers which derive their energy solely from the dynamic action of fluid columns. Type 12 in this group is the Wibu method of supercharging which depends for its functioning on the inertia of air columns in individual cylinder suction pipes of predetermined length. In this method, which applies to 4-cycle engines, the intake valves are held only partially open during the first part of the suction stroke by means of special cams. As the piston moves down, a partial vacuum of approximately 4.5 pounds is created in the cylinder. At about midway of the suction stroke the intake valve is fully opened, suddenly causing a high-velocity intake air column, which results in the creation of a super-atmospheric pressure in the cylinder due to the inertia of the air in the suction pipe. Figure 17 illustrates the installation of a Wibu system, showing the length of suction pipe necessary for proper operation. Adaptation of such a system requires only minor changes to an engine, is low in first cost and installation cost, and may be used in conjunction with other supercharging systems. Figure 18 is a weak spring indicator diagram of an engine employing the Wibu system and shows cylinder pressure during the exhaust and induction periods. When applying this method jointly with the

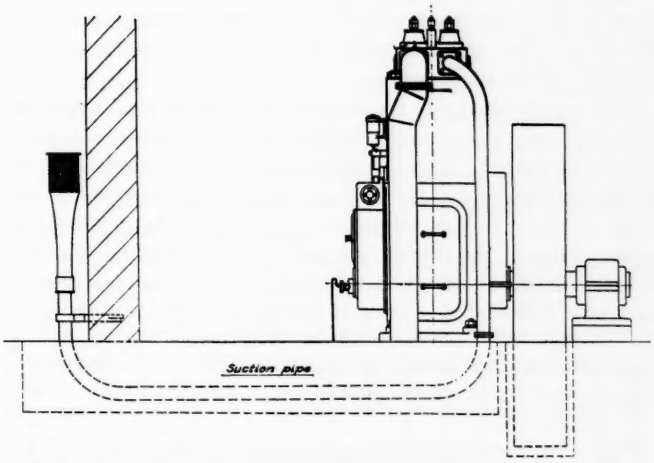


FIGURE 17.—DIAGRAMMATIC ARRANGEMENT OF ENGINE SUPERCHARGED ON THE WIBU SYSTEM.

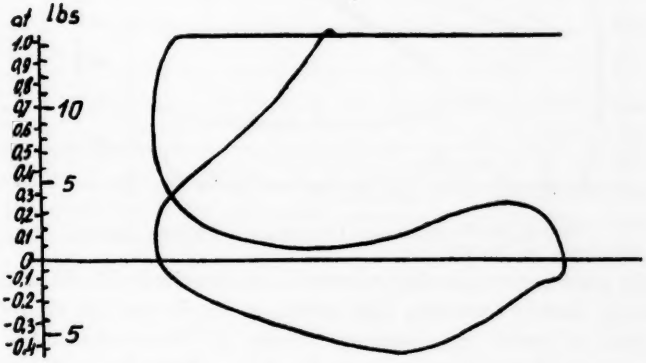


FIGURE 18.—INDICATOR CARD OF A WIBU-SUPERCHARGED ENGINE.

Buchi system, benefits of each method are realized; the dense air discharged from the turbo-blower to the Wibu type suction pipe increases the kinetic energy of the air column, thereby accentuating the "ram" effect and increasing the degree of supercharging and efficiency of the turbo-blower.

Substantially similar to the above is the Kadenacy or "harmonic induction" method of supercharging 2-cycle engines, shown as Type 13 of Table I. This method utilizes the principle of resonant pressure oscillations in the exhaust manifold as described in the Buchi system. Sudden release of exhaust gases by means of an exhaust valve of the poppet type, with proper attention to design of the exhaust passages, sets up a high pressure wave in the exhaust pipe, followed by a wave of rarefaction. Opening of the in-

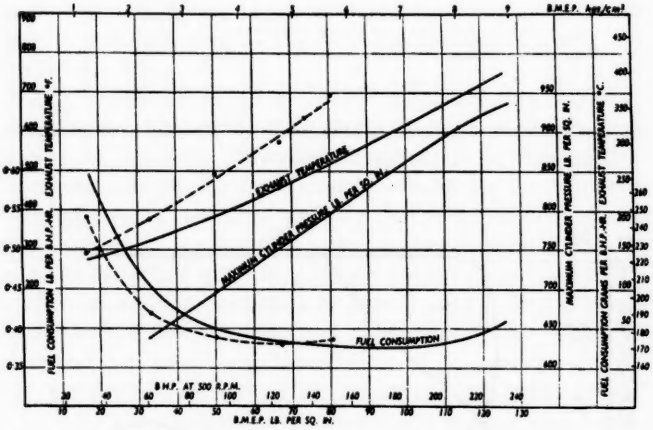


FIGURE 19.—PERFORMANCE CURVES ON A PETTERS ENGINE.

take ports in corresponding cylinders is synchronized with the latter waves, thereby producing high intake air velocity and the desired degree of inertia supercharging. Figure 19 shows exhaust temperature and fuel consumption as functions of BMEP. (or BHP.) of a Petter 2-cylinder, $8\frac{1}{2} \times 13$, 2-cycle engine, for operation as a standard uniflow-scavenged engine as compared with the same engine supercharged on the Kadenacy principle.[14] The super-

charged operation is represented by the solid curves. Referring to a BMEP. of 70 pounds, which is substantially rated load for the unsupercharged design (tests for both conditions having been made at 500 RPM.), the exhaust temperature is 610 degrees F. At the same temperature for supercharged operation, the BMEP. is 98 pounds—an increase of 40 per cent. The maximum cylinder pressure for this latter rating is seen to be 860 pounds per square inch. Furthermore, for supercharged operation, the fuel consumption is slightly better and is less than 0.4 pounds per BHP. per hour for a range of output of 55 to 135 per cent.

In recapitulation, the advantages of supercharging of Diesel engines may be tabulated as follows:

(1) Output of an engine of given displacement and rotative speed is increased without involving appreciably greater thermal or mechanical stresses, and without the necessity for extensive redesign.

(2) Fuel economy is maintained or improved.

(3) Mechanical efficiency is improved since frictional losses are very little greater and total output is increased.

(4) Unit weight, space and cost are decreased.

(5) The percentage of heat loss to the cooling water is decreased.

In conclusion let it be observed that the process of survival of the fittest is applicable to supercharging as well as to men. Time gradually eliminates the less efficient methods and ideas and also develops a large diversity of applications. Supercharging is not a universal remedy but under some operating conditions it has been widely and successfully used, and it will continue to be developed.

BIBLIOGRAPHY.

1. "General Electric Turbo-Supercharger for Airplanes," Dr. Sanford A. Moss, Am. Soc. of Naval Engrs., Vol. 32, page 586.

2. "The Importance of Supercharging," The Oil Engine, November, 1937.

3. "Progress in Supercharging," The Oil Engine, April, 1940.

4. "Diesel Supercharging—Its Effect on Design and Performance," Russell Pyles, S. A. E. Journal, May, 1938, page 215 .

5. Jahrbuch Schiffbautechnischen Gassellschaff, 1912, page 264.

6. "Supercharging Marine Oil Engines—II," The Oil Engine, September, 1938, page 219.

7. "The Present Position of the Diesel Engine for Marine Purposes," H. H. Blach, Proceedings of the Institution of Naval Architects, 1931, page 158.

8. "The Buchi Supercharging System," The British Motorship, Vol. 8, page 260.

9. "Supercharging of Internal Combustion Engines with Blowers Driven by Exhaust—Gas Turbines," by A. J. Buchi, Transactions, A. S. M. E. Section 1, February, 1937, page 85.

10. "Attributes of the Buchi Exhaust Turbo-charging System," The Oil Engine, September, 1939, page 157.

11. "A 1500 K.W. Pressure-charged Oil Engine Plant," The Oil Engine, February, 1940, page 294.

12. "Further Tests with the Buchi Supercharging System," The British Motorship, December, 1927, page 343.

13. "The Importance of Supercharging," The British Motorship, February, 1928, page 447.

14. "Increasing the Output of a Modern Two-Stroke Engine," The Oil Engine, January, 1940, page 286.

15. "The Latest Krupp Four-Cycle Engine," British Motorship, December, 1937, page 326.

16. "Performance of Supercharging Diesel Engines," British Motorship, April, 1936, page 27.

17. "A New System of Supercharging," Marine Engineer and Motorship Builder, November, 1927, page 415.

18. "The B. & W. Airless Injection Engine," British Motorship, October, 1929, page 268.

19. "A 4000 H.P. French Diesel Locomotive," The Oil Engine, May, 1938, page 4.

20. "Engineering Progress," Mechanical Engineering, July, 1935, page 437.

THE USE OF AN ELECTRICAL STRAIN GAGE IN INVESTIGATING STRESSES.*

By Lieutenant E. S. Carmick, U. S. N., Member,
and
Lieutenant H. B. Dodge, U. S. N., Member.

The authors present a brief description of the work done and results obtained in their thesis study. The article describes a very interesting application of an electrical strain gage in studying propeller design.

The trend of recent engineering design has been a great impetus to the development of strain gages. In order to measure the stresses in structures subject to high rotative and reciprocating speeds, high temperatures, and high pressures a vast amount of ingenuity has been shown. Consequently there exists on the market today many different types of strain gages, based on several distinctly different principles. By application of these devices the engineer obtains an accurate knowledge of the stress distribution in his machine under load and the existence of dangerous stress concentrations. Most promising has been the filament type of electrical strain gage, now being rapidly developed into a useful tool, applicable to a wide range of problems.

The Propeller Design Problem.

The problem chosen by the authors while postgraduate students in Marine Engineering at the Massachusetts Institute of Technology was that of investigating the stress in a statically loaded marine propeller. A further purpose of the problem was to check the existing scheme of propeller design calculations. Still further, it became our purpose to experiment with and develop a tech-

* Based on Thesis by the authors at Massachusetts Institute of Technology.

nique in the use of electrical strain gages. It is particularly the purpose of this paper to describe the course of this last phase of the problem.

In the propeller design problem there has long been used a method of strength calculation based on the beam theory. This becomes a long process of assumptions and approximations, as can be seen in Admiral D. W. Taylor's " Speed and Power of Ships," chapter 29:3. The method has proved satisfactory in the past and will continue to be useful since it errs greatly on the safe side in its assumptions. However, it does not give the actual strength of any section, nor any idea of stress concentrations. Furthermore, marine propellers of recent design, having great mean width ratio, air-foil sections, and a variation of pitch, suggest a much greater departure from the Taylor theory of design. With the possibility of even a broader field of shape and form development for the marine propeller, it seems impractical and unlikely that some new and more complicated theory of design calculations will meet the designer's needs.

Preliminary Considerations.

With need of some form of strain gage indicated, there arose the question of what kind of gage to use.

The types of strain gages available are mentioned as follows; and are also fairly representative of the entire present day field:

1. *Huggenberger*—Lever system with needle moving on a scale—gage length 1 inch to 2 inches, applied by clamping to structure—accurate to $\frac{1}{100,000}$, not very sensitive—hysteresis effects.

2. *Tuckerman*—Mechanical—Optical system, difficult to use,—clamped in place,—accurate to $\frac{1}{500,000}$ difficult to interpret in two dimensional problems, expensive.

3. *Carbon Strip*—Electrical resistance change—clamped or cemented to structure—large temperature and hysteresis effects—poor for static work—about 5 per cent error.

4. *Resistance Points*—Electrical resistance change—qualitative results, useful as adjunct to other tests.

5. *Filament Type of Electrical Gage* electrical resistance change—any gage length or form, cemented to structure, accurate to $\frac{1}{1,000,000}$ moderate temperature effects—very sensitive, cheap.

From a consideration of the various types whose characteristics are briefly noted, it appeared that the electrical strain gage as developed by Drs. A. C. Ruge and A. V. deForest would best suit the problem. Those factors especially influencing the choice were:

1. Method of securing gage.
2. Adaptability of gage to curved surfaces.
3. Ease of application and use.
4. Known accuracy and consistency.
5. Sensitivity.

This gage which has already appeared in many forms, also readily becomes a permanent installation which is an important advantage worth the slight added difficulty of application. It is desirable to point out here that this type of gage is not limited to statical problems nor to simple structural surfaces. Some of its many successful applications in the Massachusetts Institute of Technology laboratories are:

(*a*) Measurement of torsional stress in motor-generator set shafts (using filaments wound helically on shaft).
(*b*) Torsionmeters—similar to above.
(*c*) Measurement of stresses in ship structures.
(*d*) Measurement of stress in water tank plating.
(*e*) Measurement of peak stress in plating of explosion chambers.
(*f*) Measurement of drag in certain wind tunnel experiments.

Description and Theory of the Electrical Strain Gage.

The electrical strain gage depends upon the change in ohmic resistance of a conductor when its cross sectional area is changed. The fine wire filaments which are the elements of the strain gages are firmly cemented to the surface of the structure studied. If that surface is stretched, the filament stretches with

it and thereby increases in resistance. If the surface is compressed, the wire will be shortened and its resistance decreased.

The strain gage is placed as one arm in a Wheatstone bridge so that the ohmic change due to a stress in the structure can be measured. The bridge will require an extremely sensitive galvanometer and a certain relationship between circuit constants. From the ohms-per-ohm change in a given gage filament, the strain and thence stress may be calculated. The factor connecting the ohm ratio to the strain is known as the "Strain sensitivity factor." The value of this factor has been determined for many materials.

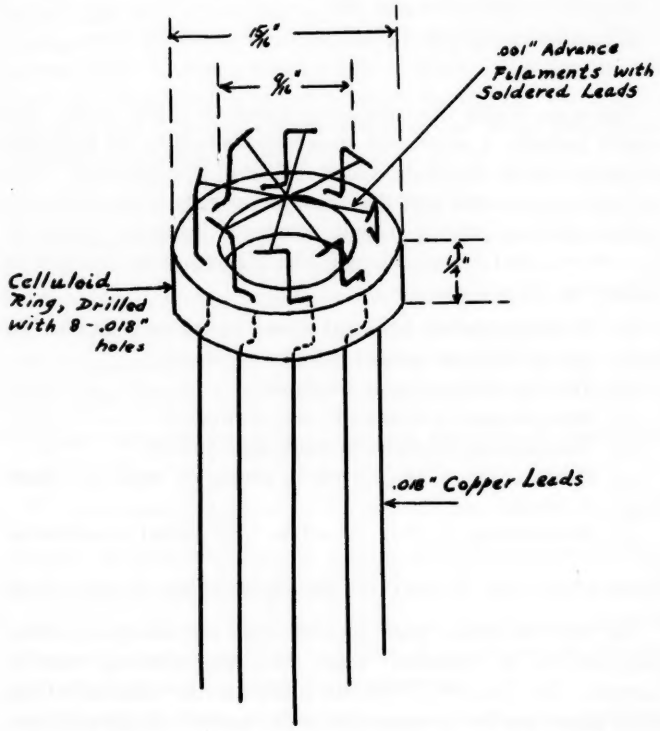


FIGURE 1.—ROSETTE FORM STRAIN GAGE USING FOUR ¾-INCH FILAMENTS.

The fine filaments are soldered to copper lead wires of about .018-inch diameter. They are then cemented to the surface of the structure. If the structure is a metal, a layer of paper is first laid down as insulation. A good grade of typewriter "onionskin" paper serves very well. The most successful cement used has been "Duco" Household cement.

It is readily seen that this type of gage may take nearly any desired form or size so long as suitable electrical circuits are designed around it. The special form chosen was the "rosette" as pictured in Figure 1.

This form was chosen since it made possible the reading of strains in four different directions at a given point. Consequently, principal stresses at each point studied could be calculated, and directions of stresses determined. This form showed great value

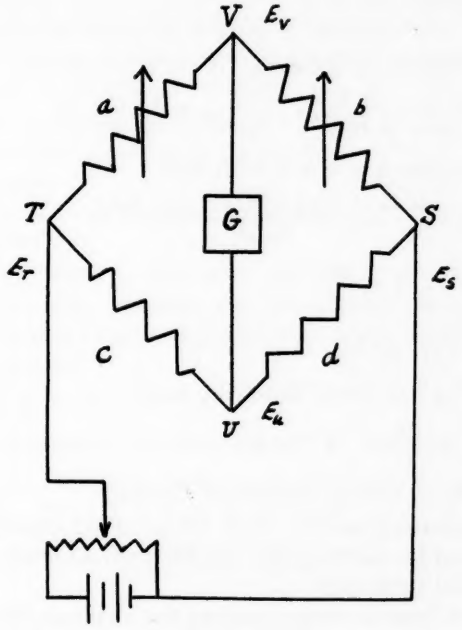


FIGURE 2.—SIMPLE WHEATSTONE BRIDGE CIRCUIT.

in other engineering problems. It has been used in studying stress distribution in all-metal aircraft wing, stresses in a ship's tank, etc.

To explain the use of the gage in more detail, let us first review the equations of the Wheatstone Bridge as pictured in Figure 2.

The Wheatstone Bridge.

By a combination of the Expressions for Voltage and Current in the various legs:

1. $$I_G = E_T \frac{\left(\frac{b}{a+b} - \frac{d}{c+d}\right)}{x + \frac{ab}{a+b} + \frac{cd}{c+d}}$$

which simplifies to:

2. $$I_G = E_T \frac{bc - ad}{x\,(a+b)\,(c+d) + (c+d)\,ab + (a+b)\,cd}$$

which leads to the following (if $a = c = b = d$)

3. $$I_G = \frac{b\,(c-a)\,E_T}{4b^2x + 4b^3} \text{ or } \frac{c-a}{a} = I_G \frac{4\,(x+b)}{E_T}$$

or if we have $a = c \neq b = d$; then

4. $$\frac{c-a}{a} = \frac{I_G\,(a+b)\,[x\,(a+b) + 2ab]}{E_T\,ab}$$

where $\frac{c-a}{a} = \frac{\Delta r}{r}$

5. Strain $(\varepsilon) = \frac{\Delta r}{r} \div$ "n"

where "n" = Strain Sensitivity factor.

6. Stress $= \frac{\Delta r}{r} \div$ "n" $\times E$

where E = Young's Modulus of Elasticity.

The minimum stress that can be measured will depend upon the sensitivity of the Galvanometer and the strain sensitivity factor of the electrical strain gage.

It is seen from the above equations that a ratio of ohmic change to ohmic resistance of a given bridge arm, lead directly to the

calculation of *stress*. Consequently, when testing with the bridge, if a balance is made before and after the resistance of a given arm is changed, only the change in resistance is required. Because of the relationship ad = bc at balance, the change in resistance of the variable arm, (the strain gage), at "c" or "d" may be balanced in "a" or "b." This is done most conveniently by decade resistance boxes shunted across "a" or "b," and in this way the resistance change is readily noted.

It is possible to make tests without balancing the bridge when a resistance change takes place, by evaluating the galvanometer deflection produced. This was experimented with and found a quicker but less accurate method.

It is to be noted that the magnitudes of current and voltage do not enter our final equations above. But their values must be controlled in order to maintain the sensitivity of the set-up and to prevent the zero point of galvanometer balance from drifting.

To illustrate the method of calculation employed when balancing the bridge for each reading; consider a circuit as shown in Figure 2 having the following constants:

a = 100 ohms (shunted by decade "S") = r
b = 100 ohms + 6000 ohms (in parallel)
c = 25 ohms
g = galvanometer, resistance = 40 ohms
E_T = 3 volts
d = gage (about 25 ohms when unstrained).

From the earlier equations, the ohm-per-ohm change from a "no-load" bridge balance (S_o) to a loaded bridge balance, (S) on the gage, we have:

To balance ad = bc

Considering change of resistance in arm "a" only;

$$a = \frac{rS_o}{r + S_o} - \frac{rS}{r + S}$$

$$= \frac{r^2S_o + rSS_o - r^2S - rSS_o}{(r + S_o)(r + S)}$$

$$= \frac{r^2(S_o - S)}{r + S_o(r + S)}$$

Then:

$$\frac{\Delta a}{a} = \frac{r^2 (S_o - S)}{(r + S_o)(r + S)} \div \frac{rS_o}{(r + S_o)} = \frac{r (S_o - S)}{S_o (r + S)}$$

or

$$\frac{\Delta r}{r} = \frac{\Delta a}{a} = \frac{r (S_o - S)}{S (r + S_o)}$$

$$\text{“n”} = \frac{r (S_o - S)}{S (r + S_o)} \div \text{strain.}$$

Considering a simple cantilever beam problem:

M = Load $\times$ Arm (in. — lbs.)

$$\begin{cases} \text{Section Modulus} = \dfrac{bh^2}{6} \\ E = \text{Young's Modulus.} \end{cases}$$

$$\therefore n = \frac{r (S_o - S)}{S (r + S_o)} = \frac{M}{(\text{Sect. Modulus}) E}$$

Such calculations as these using experimental data from simple beams having “Advance” wire strain gages, gave values of “n” equal to 2.03.

The value of “n” varies not only with different alloys but from one spool of a given wire to another, and its value must be established for each lot used. With the value of “n” determined, our solution of the above equations is for *strain* and subsequently *stress*.

Experimentation indicated only 1 per cent variation in the determination of strain while working on simple beams of rectangular section and known loading. This error was later cut down and was attributed to inexperience in manufacturing and applying the strain gages. Departure from a straight line, existence of an angle between axis of beam and the gage filament, excessive stretching of the filament wire during the gage manufacture, poor soldering of the leads, and careless cementing of gage and insulating paper will all lead to slight errors. However, granting a possibility of 2 per cent error, this is remarkable accuracy for a strain gage.

Experimentation with gages of various lengths indicated one-half inch is as small as can be conveniently worked with ordinary

hand tool skill. Below this length the solder bands between gage filament and copper leads will cause an appreciable percentage deduction from the length of the active part of the filament.

Although any electrical conductor might be employed as filament material, certain copper nickel alloys such as "Advance" and "Elinvar" exhibit the best combination of strain sensitivity factor and temperature effects. "Advance" having an "n" value of 2.2 was used in the authors' problem. "Elinvar" has an "n" value of about one and a half times that of Advance, but it is unfortunately about fifty times as sensitive to temperature. Exhaustive research in the determination of suitable filament materials has been carried out by Dr. Johann H. Meier and others under the direction of Dr. A. C. Ruge.

Special Adaptations of Electrical Strain Gage.

The electrical strain gage has in some problems been employed with a cathode-ray oscillograph. In other applications the gage has been made to keep its own graphic record. In the measurement of strains of small magnitude, vacuum tube amplification circuits have been used.

The Rosette Form of Electrical Strain Gage.

(See Figure 1.)

The rosette form of gage is essentially four gages in a single assembly. The four wire filaments intersect at 45 degree angles, the wires being secured by a tiny drop of solder at the intersection. The celluloid ring seen in the sketch served as a convenient jig during manufacture, and gave rigidity to the filament and lead assembly after it was located and cemented to the surface of the propeller.

In a case of two-dimensional stress the readings of such a gage provide sufficient data to construct the Mohr's stress plane and to determine the direction and magnitude of the principal stresses. This procedure is readily obtained by reference to S. Timoshenko's "Strength of Materials" or other standard works on the subject.

Mechanical Considerations of Particular Problem.

Since the problem was inspired largely by a desire to check the Taylor design theory, the method of loading used was static. By using a static, point loading at the center of pressure of a blade, the loading given in the Taylor theory is duplicated, and we can proceed directly toward strength calculations, having neglected only the centrifugal effects, which are not of major interest in a marine propeller and the results obtained would be compared with the theoretical calculations for the same loading without centrifugal effects. The propeller used for the test described hereafter had the advantage of being typical of the design developed in the Taylor theory.

It is admitted that a lack of time and facilities prevented an actual dynamic study of the stressed propeller in water. However, this was not necessary in order to parallel the Taylor theory of design. Nevertheless, it is felt that such a test would be entirely feasible.

Method of Loading Propeller.

The propeller was loaded by a pin carried on a heavy beam. One end of the beam was secured to a hinge plate which was locked to the slotted floor plate of the shop. The loading was applied at the other end of the beam by means of a turnbuckle, also secured to the floor plate. The set-up of this apparatus may be seen in the photograph (Figure 3).

Provisions were made in the design of this apparatus to permit the following:

(*a*) Locking the propeller rigidly in any horizontal position.

(*b*) Movement of the loading pin to bring it normal to the blade surface—then locking it.

(*c*) Movement of the loading beam relative to propeller.

The magnitude of the load applied at the pin was measured by a strain gage on the pin itself. This strain gage could be readily inserted in the Wheatstone bridge circuit to indicate any loading imposed. As a check on the validity of such procedure, test runs were made on the loading pin alone in an Olsen compression testing machine. The strain gage secured around the pin's cylin-

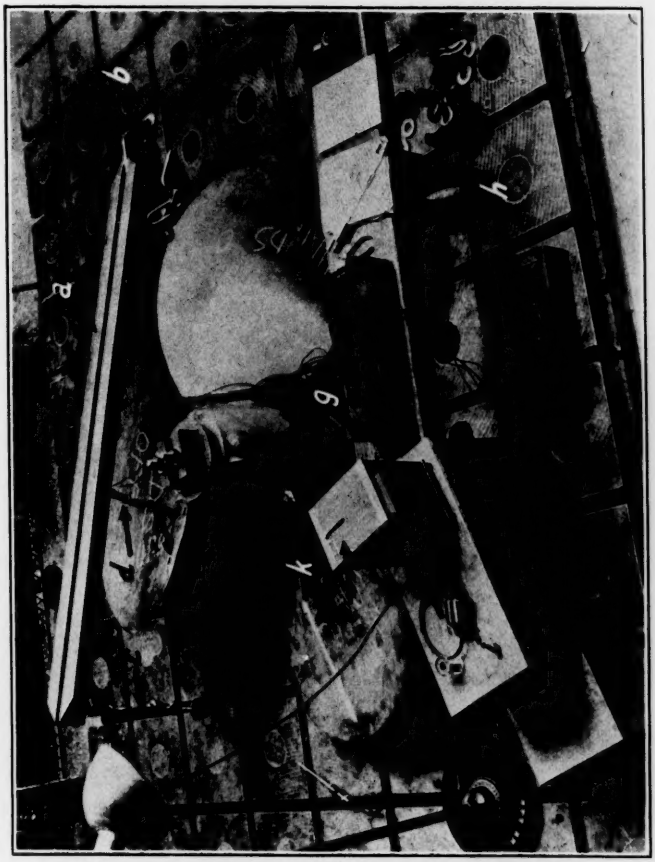


FIGURE 3.—LABORATORY SET-UP.

(a) Loading Beam.
(b) Hinge Plate.
(c) Turnbuckle.
(d) Loading Pin.
(e) Galvanometer.
(f) Wheatstone Bridge (Control Box).
(g) 3-Volt Dry Cell Battery.
(h) Decade Resistance Boxes.
(i) Transformer for Galvanometer.
(j) Strain gages.
(k) Strain gage used as "dummy." (To give bridge symmetry and to eliminate temperature effects.)

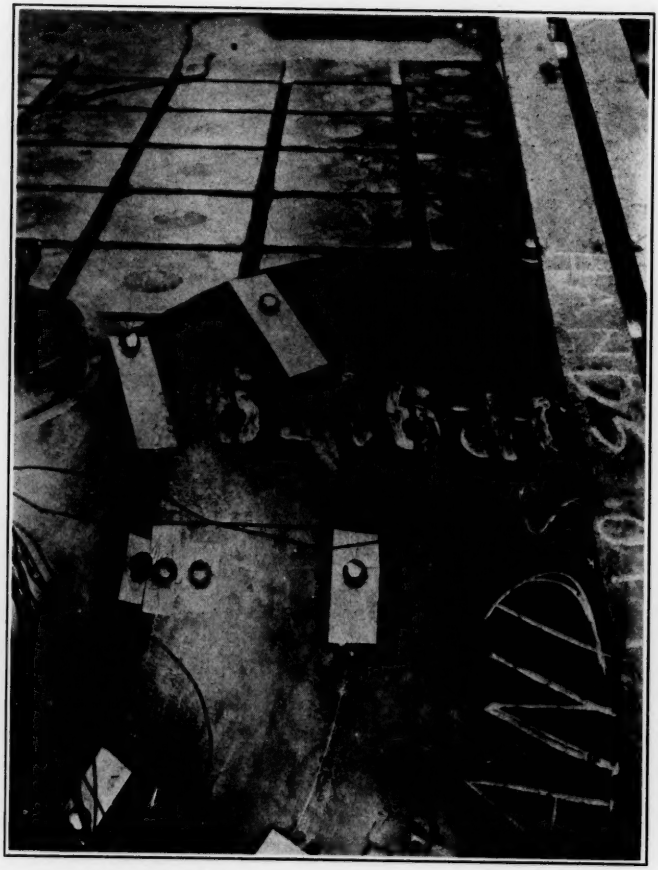


FIGURE 4.—LOCATIONS OF STRAIN GAGES.

drical surface was connected into the bridge; as loading was increased a perfectly straight line calibration curve was obtained (ohmic change versus pounds load).

The propeller provided for the problem is described as follows:

Patrol boat (Eagle boat) propeller.

(Cast by Columbian Bronze Co. Machined by Norfolk Navy Yard.)

3 blades (right-handed).

Diameter, 6 feet, 7 inches.

Pitch, 4 feet 9 inches.

Manganese bronze having Young's Modulus equal to 15×10^6, and Poisson's ratio equal to .33 (approximately), and a tensile strength of 68,000 pounds per square inch.

Weight, 1575 pounds.

P.A. ÷ D.A. = .606.

M.W.R., .40.

Hub Diam, 13.5 inches.

Fillet Radius, 2½ inches.

S.H.P. = 2000.

R.P.M., 475.

Vessel speed, 18.2 knots.

Conduct of Strain Gage Tests on the Marine Propeller.

Inasmuch as the theory of the gage has been covered, it is believed the following brief tabulation of steps will explain the testing procedure used:

(1) Fourteen rosette gages were applied to one blade; eight on the face and six on the back at points considered to offer the most useful data for the investigation. (See Figure 4.) Each gage was cemented in place so that one of its filaments coincided with a radial line through the point of application and the axis of the hub. The leads to each such filament were designated A-A, while the remaining three filaments of each gage were labelled B-B, C-C, and D-D clockwise. With this system of location and orientation, subsequent interpretation of results was simplified.

(2) A single similar rosette was cemented to another propeller blade which was *not* loaded in the tests. A single filament of this gage remained in the bridge circuit (Figure 5) at all times as the dummy; to give symmetry and to compensate for temperature effects upon the active gage.

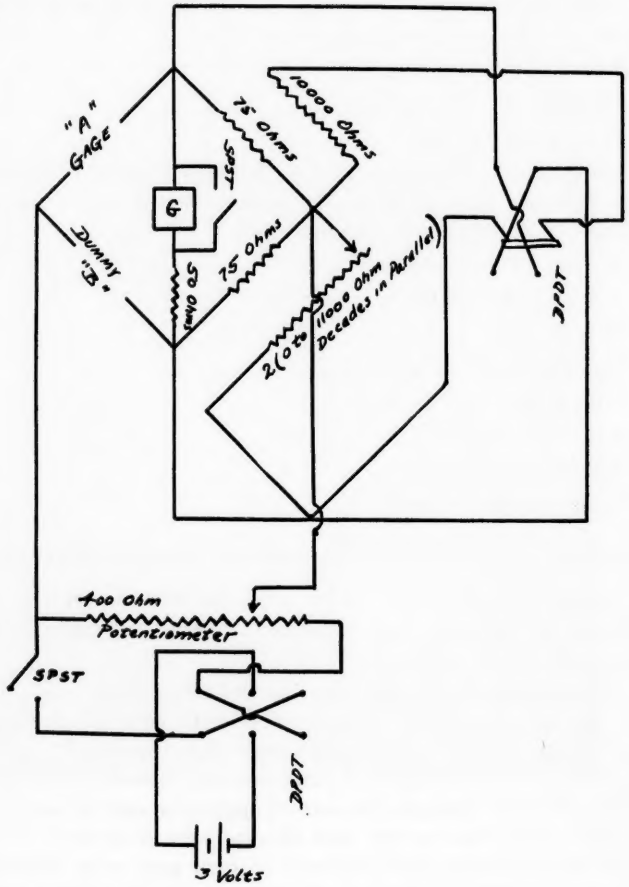


FIGURE 5.—DIAGRAMMATIC SKETCH OF BRIDGE CIRCUIT.

(3) All filament-lead circuits were tested for continuity and grounds, and their approximate resistance checked with an ohnmeter.

(4) The loading pin was placed normal to the propeller face and clamped rigidly to the loading beam.

(5) Loads up to 6000 pounds were cranked on and off by means of the turnbuckle.

(6) The leads of the various gages, two at a time, were connected into the bridge where "no-load" and "loaded" readings were obtained and recorded. Similarly, load and no-load readings for the gage on the loading pin were taken. (Tests on the rosettes on the blade showed the same linear relationship of ohmic change with load as was noted on the loading pin.)

(7) All data was then fitted to a suitable tabular form and the calculations for principal stresses performed.

Conclusions.

(*a*) *Concerning the particular problem.*

1. The experimentally determined stresses were comparable but smaller than those calculated by the theory in the central portion of the face.

2. Stresses determined near the edges and the fillet, or root section bore practically no relation in either magnitude or direction to the calculated values.

3. Stresses in the fillet were relatively small, and no stress concentrations were indicated. It appeared that the propeller had been "overdesigned" as far as metal in the fillet was concerned.

(*b*) *Concerning the use of the Electrical Strain Gage.*

1. This electrical strain gage proved both in preliminary experiments and in the particular problem to be of great accuracy, dependability and sensitivity. The sensitivity is a function of the filament material, the quality of galvanometer and circuit design.

2. The test showed the type of gage to be simple to use, and easily adapted to temporary or permanent installations.

3. The cost of equipment is considered low, about $120.00 in all for construction of the circuit.

4. It is believed that such investigations as described in this paper would prove of inestimable value for the determination of the strength characteristics of new structures or proposed forms of machine design.

ELECTRICAL INSULATION.

By Jesse B. Lunsford, Member.*

The author originally expected to complete this series in four parts. After consultation with the Editor it was decided that any attempt to compress the remainder of the material and a summary into one article would be undesirable. Hence there will be a fifth, and final, part to appear in the February 1941 issue.

PART IV—ROCKS (SYNTHETIC AND OTHERWISE).

"United They Stand."

Summarizing the discussion up to this point: (1) A dynamo is only as "big" as the character of its insulation, (2) That character is essentially one of "stone," (3) That stone may be divided into two classes—*organic* and *inorganic,* (4) The *organic* stones (complex hydrocarbons) may be *bent* or *stretched* only during their "life," (5) The *inorganic* stones (oxides usually, principally silicates), being milleniums old already, are rather too "stiff" and unyielding to serve alone, and (6) The two classes of stones have *complementary* characteristics; i. e., in the weakness of either lies the strength of the other.

In the ancient expression of "Fire boils away water—but water puts out fire" the Chinese expressed a basic idea which the author is attempting to apply today—neither water nor fire can be said to be stronger, more severe, or more important than the other—because each is able to outdo the other. So it is with the two classes of insulation, one (carbonaceous) serves as the "dam" against *water,* while the other (silicaceous) serves as a "pillar" or spacer which resists *fire* (or that degree of heat which "boils away water"). It is not a case of which is the weaker or less

* Senior Electrical Engineer, Standards Branch, Bureau of Ships, Navy Department, Washington, D. C.

important and, hence, might be dispensed with; rather it is a matter of how best to utilize both so that each bulwarks the other. In the union, is their strength.

Parts II and III having dealt ideologically with the "organics," consisting basically of the elements H, C, and O, and formed in nature through the medium of *water*, sunshine, and air (or by synthesis), it is the purpose of this, Part IV of the Series, to deal on the same ideological level with the inorganics, those everlasting stones at our very feet, those oxides of silicon and certain metals (particularly aluminum) of which it might be said that they were born of "*fire*"; not once only, but many times over during the earth's long history.

"Everything Which Goes Up Must Come Down."

In this everyday taunt of mischievous small boys, there is a close parallel to our problem of insulation. For example, the *organic* stones might be thought of as a "build-up" of carbon to such a high but relatively unstable energy level that it is impossible to maintain them there except for a comparatively short while (their "life"); whereas the *inorganic* stones represent the lowest level to which silicon and certain of the "active" metals can *fall*. The one class is "up," for a brief spell, having (in nature) been lifted up there by the sun and *water*. The other is "down," mostly for keeps, having been forced there by *fire*.

And therein lies the explanation of their relative stability. That which "*goes up*" must eventually "*come down,*" even as the small boys say. If the one class is up very high, it may have quite some distance to fall, and the descent could be "in flames"; whereas that which lies already at the "bottom" does not have any lower place to fall to. "Permanence" is thus a matter of stability or equilibrium on a low plane.

In the interests of strict accuracy, in order not to offend any stickler after the truth, and for the further reason that he does not desire to let the ancient Chinese philosophy down, the author must qualify the above brief explanation by admitting that it does not hold for all eternity; if it did, then "fire" would have proven itself to be stronger than "water" and all "life" would have to cease. In time, eons of it, even sea bottoms and mountain tops

change places; even "granite" disintegrates and, through "living" organisms, helps to produce the "organics" which can themselves be again reduced by "fire." But that first re-transformation after fire, that rising from the bottom, was through the infusion of new "energy," from the sun, through the medium of *"water."*

So the ancient Chinese were right after all—there is no absolute end, because, in time, the role of the conquerer and the conquered are reversed—there is the build-up and then the tear-down, each feeding upon the other. And so also is the ubiquitous small boy right in his analysis of bodies tossed upward—the difference in viewpoint is merely one of relativity—the cycle or time-span involved.

SYMBOLISM.

The author recognizes the fact that catch phrases, even ancient proverbs, are not the best medium for the full and accurate expression of scientific truths; such truths have too many facets to permit a view of one side only to give an absolutely correct picture of the whole. Oftentimes, however, the simplest form of a picture; i.e., a "poster," does serve to convey a general idea better than an exact photograph could do, because the poster can emphasize the basic or governing features and symbolize these, free of those inconsequential (and often confusing) details that may, for no reason beyond mere happenstance, be present in the actual photograph. The author chooses, therefore, to employ symbolism in order to focus attention on those ideas which he believes to be of primary importance, despite some sacrifice in minor details; and he hopes that the reader will bear this in mind.

And, despite the numerous references and some remarks on "natural rocks" herein, these are not, for several reasons, the main subject of this discussion. The first reason is that practically all of the natural rock insulators have been used and studied for a long time back; the situation with regard to them is practically static, no "progress"; the rocks of 1,000,000 years ago are little different from those of today, and it will be the same story yesterday and tomorrow. Secondly, nearly everyone has already written about them. Thirdly, there is little we can do about them. So, it is not intended that this be a discourse on "natural" rocks, as such.

But there are lessons we may learn from these natural rocks—lessons we could learn from no other source. Just think of it in this way—we "kid" ourselves about how much we learn in our "laboratory" tests,—the tests that last only hours, or days; and once in a great while, the tests that may cover weeks or months. But these, at best, represent such a short span of time.

Why not consider the Earth—nature—and that sort of thing as a great *proving ground,* a greater "laboratory" than man may devise—time measured in millions of years, not just weeks. Certainly we might absorb some ideas as to "permanence" from such a study. And "permanence," as stated hereinbefore, is not only the central theme of this discussion; it is the very backbone of the "horsepower" rating of electrical machinery.

And another thing—we do not always have the natural rock we most desire for a given application right in our own back yard—it may be in enemy territory. Or it may be, like the asbestos in Arizona, too far from a good railroad. Or it may be that the "cheap labor" is in far away India. There are lots of things that do not just suit us entirely, and we may desire to "do something about it." In that case, we may desire, in our plan to "make our own," to learn what is best to be done and what best to be left undone. What better, long-time test data—what more independent, unbiased and revealing "laboratory"—than Nature's own? Verily "lessons in stone."

NATURAL ROCKS.

Referring to the tabulation of insulating "rocks" given in Part II, let us examine first those occurring in nature, and which, aside from the normal selection, cleaning and forming necessary to apply them, are or could be employed without benefit of synthesis. These may be listed as follows:

asbestos
aluminum oxide
calcite
chalk
clay
feldspars
granite
gypsum
marble
mica
quartz
slate
soapstone (steatite)
sulphur
talc

Obviously, these are not all of the same order of merit as insulators; and the difficulties and/or routines in their preparation for an application to specific uses will vary widely. But the essence of their listing as *natural* is that they undergo no molecular rearrangement in this preparatory processing. For example, marble, quartz, granite, and slate need only be cut to size, and soapstone requires heating; asbestos must be cleaned and shredded for handling as a textile; mica needs to be trimmed, split, and sometimes "pasted"; while the remaining stones on the above list may require compacting, shaping, and heating (or fusion) for the particular use.

It is not, of course, intended to imply by the above listing that each of them is to be used alone; on the contrary, several may be combined mechanically to produce a mixture or a combination more suitable for certain specific uses. As long, however, as such mixing results in no chemical reaction and no new compound is formed, the mixture and each of its components is still a *natural* inorganic rock.

Nor does the fact that one or more of these natural rocks are used in combination with an organic insulator necessarily change its basic character. For example, certain of these are used as inert "fillers" or adulterants in natural rubber or asphalt or even in synthetics. When, however, an element like sulphur is used to produce a molecular change in an organic material (natural or synthetic) the picture changes. If and when two or more of the natural rocks are combined in such proportions and under such conditions as to bring about a new compound, not ordinarily found in nature, then it becomes a synthetic rock. But we will come to that phase later; first, let us examine the natural rocks, to see what makes them so natural.

Let us take, for example, such natural inorganic insulators as quartz, mica, asbestos, lava, granite, feldspars, sand, clay, etc. These are *oxides* already; the "fire" of ages ago has already had its chance at them; hence, there is nothing left to *burn*. According to the ancient Chinaman, it is now *water's* chance to do something about it; in fact, water may have been trying to do just that for a long time.

A quick glance at the water solubilities of these rocks will, however, show just why it is so natural that they should exist as they do. Their solubility in water is so very low, relatively, that they are not readily disposed of by that route; that which might have been "leached" out by water to form a conducting electrolyte has, for the most part, already found its way down to the sea. So one would just naturally not expect that which is left to have good conducting properties—these have been extracted already. And the lack of such conductivity is the essence of a good insulator.

So, that which is at our feet (if we do not stand in the sea) represents, as it were, the debris of the fire, and centuries of the wind, the sun, and the rain; it is just naturally tough. Being the remnants of many lifetimes, what else could happen to it in the brief span of our lifetime; or the lifetime of a ship, with which we are chiefly concerned? Since they are already at rock-bottom, it will be right hard for them to *fall* any farther. So, we may start with them as a foundation and build upon that.

MANTLE ROCK.

Reverting again to the "interesting things about rocks" referred to briefly in Part II, the *oxides* of three "active" metals, together with that of *silicon,* combined as "silicates," account for almost 89 per cent of the earth's crust (mantle rock). If we add to this list one more metal (potassium), thus covering five oxides altogether, we arrive at over 91 per cent of this crust. These, as *silicates,* form the best and most permanent electrical insulators we know of.

Now the interesting thing about this *availability* and *permanence* line-up is that quartz (SiO_2) is not only about the best insulator of the lot, but it is also about the least water-soluble mineral on earth. It is in the very hardest class ("precious" stones), and it is chemically so stable, so "satisfied" that it is reported to be the only mineral found in all soils everywhere. In its various forms, and including mechanical mixtures, it averages more than 80 per cent of the earth's crust. With that degree of *permanence* in mind, that one time popular song about "when the sands of the desert grow cold" is a gross understatement of what could be a long wait—what if the song had, instead, said ". . . dissolve"?

Next after quartz, both as to the heighth of its electrical qualities and as to "permanence," come the best electrical *micas;* these take such readily oxidizable metals as aluminum, and potassium into the combine (as the aluminum-potassium silicates and the potassium-magnesium silicates, etc.).

In a world which now offers to explain the composition of matter in terms of energy and energy levels, such a correlation of the dielectric properties of inorganic insulators with what might be termed their "self-satisfaction" is most interesting. The "juice" does not get much of a chance to "go places and do things" if everything at home is satisfactory (no alluring "affinities") and if the holding "bonds" are strong.

And so on down the list of minerals in the earth's crust—headed by *silica* (SiO_2) and alumina (Al_2O_3)—that which is as good electrically as the designer would like; is so hard, unyielding, and indestructible that we cannot always nor so readily "bend" it or "stretch" it to our will. If we would increase its workability, as for example, by the inclusion of sodium and/or calcium, the water solubility may be increased and the dielectric properties decreased.

Let us try to express the same general idea a bit differently; for example, suppose we list the eight chemical elements comprising over 98 per cent of the earth's crust in the following relative order of merit, as it were:

	oxygen	47.33	
	silicon	27.74	amphoteric
active metals	aluminum	7.85	amphoteric
	magnesium	2.24	
	calcium	3.47	alkaline earth metals
	potassium	2.46	alkali metals
	sodium	4.50	alkali metals
	iron		

Now let us take a good look at the above line-up. Starting at the top we note that the first two elements in combination (SiO_2) as shown previously, is also at the very top in dielectric properties and in resistance to any changes through the action of water (it being the most stable and least water soluble of all minerals).

Now take the next *oxide* in line, the oxide of the first of the "active metals" on the above list, *aluminum*. Anyone familiar with pure alumina or the present-day anodized finish on aluminum alloys will recognize its quality as a dielectric; as likewise will those familiar with the unusual characteristics of a certain brand of aluminum-oxide lightning arrestors. Or let us take the natural mineral *corundum* (Al_2O_3) (abrasives, rubies, and sapphires). Not much more hope of "bending" or "stretching" any of these than there was of quartz.

Nor do we have to look far afield for another material (kaolinite) familiar to most of us in the form of "porcelain" objects, with the element hydrogen as an additional partner. This one of the aluminum silicates is also a hard and unyielding customer; it has to be to withstand the voltage, the sun, the wind, and the rain as it must when in the form of "insulator" strings on transmission towers, it keeps the high tension "juice" from going where it should not.

As we go on down the list of "active" metal *oxides,* these may be excellent insulators dry, but not so when wet. Since this listing is in the direction of an increasing basicity, and the oxides combine with water to form hydroxides, in the order of increasing ionic concentration, the reason for the loss of their dielectric properties is obvious. Since *water* and all of its doings is, as stated hereinbefore, a fundamental consideration in the naval service, there is not much hope of relying upon oxides, as such, below the aluminum oxide (Al_2O_3) *alumina*. Below this point it becomes a matter of combining one or more of these elements (in the descending scale) on the list, with silica, to form a *silicate*.

As we proceed down that list of "active" metal oxides, adding the *magnesium* or the *potassium* or *calcium* components to the "silicates," we arrive at certain other familiar figures in crystalline form, the several forms of mica and asbestos, some of which are much better dielectrics than are the others. The essence of their dielectric properties resides, however, in their hard, *"crystalline"* or hard, *"glassy"* forms.* Just another way of saying that we cannot keep our cake and eat it too; if we want the highest electrical properties we must take that hardness, that density or "fixity" of molecular structure which goes with dielectrics in the

solid (crystal) form, or in those amorphous (glass, porcelain, etc.) forms which, as supercooled liquids, are normally used at temperatures away below the point where they become highly mobile plastics or liquids.

* Note! In this general connection, and in order to keep the record straight, it might be well to break into the stream of thought, briefly, to point out that:

(*a*) The same *composition* may exist in as many as three *solid* forms; i.e., the crystalline, the amorphous, and the granitoid form; each of these forms noted for its *fixity* of arrangement. A common example of the oxide of silicon (SiO_2) in two forms is: (1) *quartz* in crystals, and (2) *agate* in the *amorphous*. The *form* is, therefore, a matter *of the rate of cooling.*

(*b*) Doctors disagree as to whether certain glassy rocks are simply "super-cooled liquids" or "true amorphous solids" with definite melting points. If glass is "perfectly elastic" how could it be other than a true solid? A true plastic such as asphalt has no elasticity.

(*c*) Certain other elements, relatively more rare in the earth's crust, but in the same groups of the "*Periodic*" system, have been slighted in this discussion. For example, strontium, barium, beryllium, titanium, and many others. Boron is sometimes substituted, in part at least, for silica. But let everyone take his own look at the Periodic system.

(*d*) Since silica (as SiO_4) is utilized as the basic building block in this series of inorganic insulators, the discussion has centered on tying this in with the metallic oxides on the side of increasing basicity. There is no point in going away from the amphoteric in the direction of increasing acidity, because there are no insulators of a satisfactory quality (in terms of the action of water) known to the author, nor found in nature's bag of tricks. For example, sulphur, either pure or as the oxide, may be an excellent dielectric dry but add water and we have an acid electrolyte. Likewise, when we go further, as in the direction of the halogens.

Such side-excursions as the foregoing do not, however, alter in any essential respects, the general picture the author is trying to paint. As stated hereinbefore, this is a "poster," and only the

" big-shots " in the element line-up are being sketched in. If there is anything further which these side-excursions might tend to raise it is the following:

If the essence of their dielectric properties does reside, as the author believes, *in the hard " crystalline " or hard " glassy " forms,* then might it not be said that the *closer we keep within the amphoteric range, the better will be their dielectric properties* (as well as their permanence)—and, further, *that we only depart from that on-the-fence region insofar as it may be necessary to attain workability, because this departure represents a sacrifice both of dielectric quality and of permanence.*

WHY THE SEA IS SALTY.

Now suppose we take another squint at that line-up of the eight elements comprising over 98 per cent of the earth's crust—what do we see? We see that the sea is very *salty.*

Does not that fact suggest to you another angle to the *permanence* idea about which this series of articles centers? Does it not suggest to you the possibility that certain of the metallic oxide constituents of the natural rocks have, relatively, less permanence than do others, at least where the action of water is concerned? What took them down to the sea?—rain *water,* of course.

In that eight element line-up it will be observed that, starting at the top and excepting iron, the grouping as a whole exhibits a decreasing order of acidity and an increasing order of basicity. The element iron is placed at the bottom of the above list merely because of its decreasing order of merit as an insulator rather than because of its line-up in the other respect; those silicates containing iron, as in certain of the mica and asbestos compositions, are grossly inferior in electrical properties to those other complex silicates in which iron is absent or represents only a trace. Those natural silicates exhibiting the best electrical properties, second only to quartz, embrace the aluminum-potassium and the magnesium-potassium silicates. So, taking the chart as a whole, and evaluating the combinations on the basis of stability or permanence, dielectric properties, basicity, and water solubility, the relative merit or general desirability is about in the order shown.

From oxygen at the top of the list, down through the *alkaline earth metals* and the *alkali metals* we can guess why, in lands with good rainfall, the farmer needs to "lime" his soil and to include "potash" in his fertilizer. Also, we may guess why the sea is *salty*.

SYNTHETIC ROCK.

And, by the same token, if we would seek to learn which is, relatively, the most permanent or stable; which oxides (having been born of "fire," as it were) are the least affected by "water"; then might we not take a "lesson" on what it is that washes down to the sea? If we are to build rocks to serve our electrical purposes even better than most natural rocks now do, then must we not synthesize them from those oxides which have the least tendency to dissolve in water and wash into the sea?

The ultimate solution is, of course, not so simple as all this; but if these simple analogies do have any bearing on our present problems, then might they not serve to lend direction to our attack; might they not point out which things in nature should be emulated and which should be shunned? After all, the "life" tests carried out in nature do cover a wide scope, both as to diversity of materials and conditions and as to the time spans involved.

The next question which might arise is, "What is this *synthetic* rock?" to which the author refers. The exact definition might involve considerable discussion and some differences of technical opinion, so it might be better to list a few examples, as follows:

(*a*) Porcelain (in many compositions and forms, including vitreous enamels).

(*b*) Steatitic Ceramics ("alsimag," etc.).

(*c*) Cement-bound asbestos ("Transite," "asbestos-board," etc.).

(*d*) Glass-bound mica ("mycalex," etc.).

(*e*) Clay (in the fibrous form "alsifilm").

(*f*) Glass (in many compositions and forms, including the fibrous).

The use of such terms as "synthesis" and "synthetic" as applied to "rocks" is not intended to add glamour or to play up

mystery; it is merely the author's desire to avoid the use of such a term as "artificial" to distinguish between man-made rocks and the "natural" varieties. The term "artificial" has, by common usage, come to mean something that is not so good as the "original and only genuine"; whereas the author is striving to point out that man, by studying nature and applying its "lessons," is endeavoring to produce things which are the equal and in some cases are *superior* to those originals, at least for man's purposes.

Nor, in spite of their journalistic flavor, and current vogue, are such words as "synthetic" and "synthesis" intended to imply "newness." Glass is not new; when the first savage strung some obsidian around his neck or from his ears a long time ago, he was looking at something already old beyond ordinary measure of time. And when the first desert Arab found some smooth, shiny substance beneath the cold ashes where his last camp fire had been, it was nothing new to the world; it was merely something the Arab didn't know all about.

The term "synthesis" simply means that it was "planned that way" by some one who at least did know a little something about his subject and who had endeavored to do something about it. The glass blobs beneath the desert Arab's fire might be "artificial" rock, because no knowledge of the product went into their making; there was no selection as to what constituents should go into the brew and what should be left out; there was no technique as to temperature, time, or other condition affecting the quality, nor was the finished product predictable or controllable; it was merely "different," without any well defined plan or reason. By the term "synthetic" rock, the author means one that has been concocted according to a definite plan, based upon a reasonable knowledge of the w*hat*, the *how*, and the *why*. It does not guarantee perfection, but it does mean that the quality is dependent upon knowledge rather than upon mere chance.

BY WAY OF ILLUSTRATION.

As in the case of the organic rocks discussed in Part III of this Series, so it is with the inorganic rocks; the field is too large, too well covered already, and it would not be in keeping with the ideological character of this discussion to go into detail on each

class of inorganics. Some one class must be chosen as an example, as typifying in some fashion the strengths and the frailties of all.

For the purpose of such illustration, the author will take *glass* as something to talk about; *not* that he has any glass to *sell,* but merely because it is easier to fit it into the general picture. Since "Part III Organics (Synthetic and Otherwise)" of this series had to do with *resins,* as a form of *carbon,* it is but fitting that its inorganic counterpart in the insulator field, *glass,* be chosen as the form of *silicon* to be discussed in more detail as the principal subject of this, Part IV of the series.

Before getting down to glass, however, it might be well to make brief mention of porcelain, steatitic ceramics, cement-bound asbestos, glass-bound mica, and fibrous clay; not by way of adding anything to the general store of knowledge on them, but rather, to lend point to the central theme of this discussion; to show the relationship of one to the other; and to show how the author "got that way."

PORCELAIN.

Porcelain was, early in the history of electrical development, recognized as an excellent dielectric; it still is, for land installations. In the early days of electricity aboard naval vessels it even had quite a vogue. It had one fatal weakness—its impact strength under naval "shock" (impact) conditions (rapidly changing acceleration) just wasn't—and shortly thereafter, all naval specifications for electrical equipment read something like this: "Porcelain not permitted." It was too unyielding, mechanically, and hence, was supplanted by other materials.

As time went on and the use of electricity aboard ship further increased, there were certain applications (resistors, etc.) where nothing elese could seem to take the place of porcelain, certainly not from an economic viewpoint. Take a resistor, for example, where extreme degrees of heat must be tolerated; pure (untreated) asbestos or mica splittings would serve satisfactorily while too hot to hold water in the interstices, but when the apparatus cooled down, the interstices soaked up water and resulted in high leakage currents or grounds. If there were no insterstices or slippage

planes provided to permit the necessary bend or "give," one was no better off than when using a *solid mass* like porcelain. If, on the other hand, the interstices between asbestos fibres or mica laminae were then filled with a yielding, organic material to stop water, then the permissible temperature limit of the organic binder acted to limit the permissible operating temperature—the design would thus of necessity be too large and heavy.

So, whatever the starting point, one revolved around and round in a circle. It was finally decided not to continue the ban on the use of porcelain as electrical insulation aboardship, but rather, to limit its use along lines somewhat as follows:

(*a*) Use it only where no other material would serve as well, and

(*b*) Where used, require that its shape, proportioning, and method of support be such that the shock of the vessel's own gun-fire, or the shock resulting from a hit on the vessel (not, of course, a direct hit of the object) would not transmit any undue strain to the porcelain itself—the support or container of the porcelain to take the strain instead.

Obviously, such restrictions, necessary as they are from a naval viewpoint, do not help the cause of porcelain as a class of material. Yet, in other respects, and for other (non-naval) applications, porcelain is an excellent material. It is to be recognized, of course, that the term "porcelain" covers a wide field. For the purpose of the foregoing discussion, however, the non-give feature under high shock conditions is a fatal weakness. This fact is brought out here merely for the purpose of highlighting one of the principal features in this general picture of solid insulation which the author is trying to paint.

STEATITIC CERAMICS.

Ceramics or the potter's art in working in clay is likewise too large a field to cover in a few sentences. In fact, all porcelains are likewise ceramics, but all ceramics are not porcelain. In making the steatitic distinction, however, the author merely has in mind the narrowing down of the discussion to the "steatites." There are both natural and synthetic steatites; the one you take as

is and drive off water—the other you exercise some judgment as to what goes into the brew (or what is left out, depending on how one looks at it).

One brand of natural steatite has been known for so long as "Lava" (a trade name) that one might think of it (mistakenly) as coming out of the mouth of volcanoes. It isn't quite that bad, although it is *fired* (when ready) to make a very hard insulator, excellent for certain purposes. The same manufacturer has, however, identified his synthetic steatites under the general trade name of "Alsimag." Note particularly the various parts of that trade name, the *Al* for aluminum, the *si* for silicon, and the *mag* for magnesium; in other words, a "proportioned" silicate of the aluminum-magnesium variety. If the reader will refer back to the little table of elements in the Earth's crust, and their relative order of listing in terms of water solubilities (low) and electrical properties (high) as given near the beginning of this article, he will note that "Alsimag" sounds like an awfully good name. If it just lives up to its name it could be a very "permanent" dielectric, once it has been "fired" to drive off the "water" that enabled it to be fashioned to final shape.

Obviously, as a class of ceramics, such synthetic silicates, whatever their excellence in other directions, might be expected, like the porcelains, to have little if any "bend" or "stretch" in them. Consequently, these materials are subject to certain limitations in respect to naval shipboard applications—the principal ones being the design, the shape, and the method of mounting necessary to minimize the possibility of fracture due to "shock" of impact (rapidly changing acceleration), and also the matter of keeping water out of interstices and off the surface (impregnation and/or glazing).

CEMENT-BOUND ASBESTOS.

Or, let us take another of these hard stones. In the early days of electricity aboardship, the first switchboards and panels (and such bases as were not of porcelain) were of the natural rocks, *slate* and *marble*. Both of these materials, being of low and non-uniform impact value, had to be supplanted by more dependable materials. Furthermore, there was the matter of conducting

veins, striae, etc., which affected the electrical homogenity as well as the mechanical.

In order to increase the impact value, as well as the electrical uniformity, resort was had to a *fibrous* structure; the fibres being asbestos laid in portland cement. (Note this admixture, mechanically, of the silicaceous compounds, to make up for natural weaknesses). Then, in order to seal against *water,* it was necessary to completely *impregnate* this composite structure with an *organic* insulating compound.

This composition, or rather, the performance values required of it, took the place of the natural rocks, *slate* and *marble* for switchboards, panel boards and large bases, in the electrical distribution system of vessels. There is no need to go into this matter further at this point, because the technical aspects are covered fully under N. D. Specification 17-I-6 of the current issue. It is mentioned here merely to show the path by which the author has arrived at certain way-stations on the road to his philosophy; and to illustrate the point that the more things seem to differ, the more they become the same thing—just different facets.

GLASS-BOUND MICAS.

Another of the synthetic stones which illustrates more of the same thing, yet has somewhat different virtues and different limitations, is the combination of mica flakes and glass; the former being complex silicates in the crystalline form and the latter being silicates in the amorphous form. As in the case of the cement-bound asbestos discussed hereinbefore, there is a virtue in the mixing, mechanically, of the crystalline and the amorphous forms, even if these two different forms of the same thing (silicates) are cousins, or even blood brothers as it were.

There are certain naval applications where this class of materials is now in use; and there are probably other uses to which they can be applied as a result of more careful study and investigation. They are mentioned but briefly at this time, not because of any extensive naval experience with them, but rather that their chemical composition and general attributes seem to fit in with an ideological discussion such as this.

FIBROUS CLAY.

Bentonite clay is another of the old-timers right down this ideological alley. At some time or other, away down the dim and distant past, it started out as perfectly *new* volcanic *ash*. The "*fire*" literally blew it into the heavens. After settling down to earth and being kicked around by "*water*" (by the rain, the snow, and the ice) for some millions of years, it has "fallen apart" still farther. Until finally, it might be thought of as clay which has been so weather-beaten as to be "plumb wore out." Not enough energy to hold itself together—worse even than the "mountain-boys" in the funny papers.

But there is some hope left if its dire plight is given some constructive thought—because the bentonite clay represents the "survivors" of this awful punishment. Both *fire* and *water* have had their full say, and it is the tough customer that still stays on. In "smaller pieces," yes, and rather "disorganized" too, but that which is left after all this punishment must have something that nothing else on earth has—staying power. Look back at the tabulation near the beginning of this article, and note the relative order of merit as to water resistance and dielectric quality shown for certain elements of the earth's crust.

Now, in its totally disorganized state, down but not beaten, this clay of wrath is not much to stir ones imagination. But with a little water and some agitation, a colloid (jelly to you) is formed. Given a course in setting-up exercises under proper supervision, followed by massage, and we have a fibrous paper—a "rock-paper," if you will. No "stretch" to it—and whose only ability to "bend" is just that of glass or other inflexible things to bend, if thin enough.

The author does not know anything about "Alsifilm" but what he has read, so he will polish off his remarks on this subject in a hurry. At the same time he cannot help but point again to "Al" and "Si" (in the form of silicates of course) and their so unusual behavior; and to say that in the choice of the name "Alsifilm" the inventors coined a word that seems to symbolize, in part at least, the author's own philosophy as preached herein. Whether or not we are in complete agreement on that score depends upon whether or not these synthetic inorganic rocks are thought by their

inventors, to "have everything"; the author's own philosophy stops before he gets that far.

GLASS.

Now we come to "glass," as the main subject of this discussion. There are several reasons for this. One is that it is such a loosely defined field that one could talk about almost anything within its vast confines without being brought up sharp by critics. However wild a statement might be, the field is so large that by proper "interpretation" it could be made to fit some place in that field. Now how about a definition for glass somewhat as follows:

"An inorganic composition of silica and/or alumina, together with one or more metallic oxides, which has passed from the liquid to the solid phase without crystallization; i.e., a super cooled liquid or an amorphous solid." This definition covers a lot of ground—are there objectors?

Secondly, since sand or granite or marble or asbestos or mica, or almost any other such silicaceous rock would, if melted and then cooled down too rapidly to permit recrystallization, become "glass" by almost anyone's definition, then glass might be thought of as a "*phase*" of silicaceous compositions rather than as any definite silicaceous composition in itself. In other words, might not glass be thought of as a *thwarting* of the tendency to crystallize, brought about by the temperature, by the internal friction (viscosity), and time relationships involved in cooling down below the liquid phase? Or to state it still differently, is not glass a *phase* of substances rather than the *name* of one?

Whatever your answer might be, even if it were to "shoot the author," it does not alter the general idea that glass could be representative, in its chemical constituency, of almost every kind of rock known; and that, therefore, it could reflect in degree rather than in kind, the faults and the virtues of all the other forms of rock. It would seem that the only major exception would be mica, where the crystals are in the form of very thin planes. Glass fibers can emulate asbestos fibers, but nature has man stumped on the "plane" idea that is mica. So let us pass up mica on the analogies with glass; mica got that way through *water,* over too long a period of time for man to duplicate, for the time being, at any rate.

GLASS HISTORY.

The history of glass is old, and most of its phases have been covered by many previous writers. Suffice it to say that it has been known and made use of by man for several thousand years. Whether this early knowledge stemmed from a desert camp fire or in the manner of the "roast pork" of Chinese fame is of no electrical significance. The "glaze" on earthenware vessels (pottery) of some few thousand years ago might have been in earlier recognition of the value of the glaze on porcelain insulators of today and of our present search for a good inorganic impregnant and coating of today—one that will "bend" or "stretch" such as we need but have not attained.

Also, glass shared with amber the electrical honors, as holders of a bound charge, in those earliest days when electricity was a mystery spirit to be toyed with, before it became a very ordinary sort of servant of man. The "amber" was an "organic glass" just as the melted and solidified silicaceous stones are "inorganic glasses," or simply "glass." The two glasses, one a *"carbon"* glass and the other a *"silicon"* glass, have much in common, historically as well as electrically.

There is another historical aspect of glass which might be interesting to review now that we are talking about glass "fibers." The first such glass fibers were not produced by man at all—Nature blew them out of the mouths of volcanoes. Nor was man even the first to see their value—some birds on a volcanic isle spotted them first and, lacking the usual grass, twigs, string, etc., have used them as nesting material—in fact, they have been laying their eggs in rock fiber nests for a long, long time. These birds do not have any tendency to go modern; it is simply that "rock" fiber (glass to you) was the only good nest building material available to them. A matter of necessity rather than choice. So, when the modern home maker puts some "rock wool" in the walls and under the roof of his own home today, to make a cozier nest for himself, he need not think that he was the first one to use rock in that form. This "natural" rock wool used by the nesting birds is sometimes referred to as "Pelee's hair."

It is doubtful, of course, if Pelee's hair had anything to do with the use of fibrous glass as electrical insulation. Somebody, a long

time ago, got the idea of using glass fibers for this purpose; and a number of patent applications on the subject were taken out, and even allowed to expire many years before any use could be made of the idea. The difficulty, of course, in the ability of these early inventors to utilize glass fibers was not that there was anything wrong with the idea itself, but rather, that it was too difficult to produce it at a price which would enable anyone to take advantage of it. So, our use of such glass fibers today is not a brand new thought—it is merely that modern production methods have now caught up with an old idea, so that the old ideas can actually be put to work.

Accounts differ as to what gave man the idea that "glass" or "rock" could be drawn into fine fibers so that it could be used as a textile. Even glass dresses were made a long time ago. Again, it is doubtful if "Pelee's hair" had anything to do with this though because of the geographical distances involved. It is more likely that someone had drawn out fibers of glass in the plastic stage much as one today can draw out long fibers of sugar when he is "pulling" molasses candy. Obviously, the difficulty of getting any great production of fine fibers of uniform diameter by any such means, would be a barrier to its use.

Eventually someone got the idea that if he could step up the speed of pulling and reduce the difficulty of it, such as one employs in the drawing of fine wire (minus the dies, of course) the thing might work. So, it is recorded that comparatively fine filaments of glass were at one time drawn by a man (maybe it was a boy or woman) mounted on a bicycle, the while peddling like fury.

Later, as the spraying of paint and even metals came into vogue, it seemed like a good idea to spray molten glass on objects or surfaces. Of course, the thing did not work well that way; the glass simply blew out into long, fine streamers. In short, when one uses a forced draft to blow out fine glass fibers, he is getting back to "Pelee's hair" again; because that is exactly what the volcanoes did. So, even the most modern production line methods on glass fibers are but an adaptation by man of something Nature did quite a long time ago.

If one thinks of "Pelee's hair" in connection with one method of producing glass fibers, he immediately thinks of a "circus"

and the "cotton candy" idea in connection with clay fibers. In short, what the author is trying to point out is that not only is the old saying "The more things are different the more they are the same thing" applicable to the various forms of rock in the earth's crust; the same thing holds true in the production of their fibers.

With the foregoing as a background, merely to show the kinship of glass with all rock; and the production of glass fibers to the production of other fibers; the author will proceed with a pictoral description of how glass fibers are produced in a modern plant. Everyone has heard so much about "glass," most people have seen it and wondered at it, and a large proportion of the electrical engineers in the country have probably studied in some detail the voluminous test data now available on this subject; so maybe some pictures with explanatory remarks might be of more general interest than a lot of "dry" data.

The Navy first played around with the idea of using glass in electric cables and as separators in storage batteries many years ago. The glass fibers for this work were, in the beginning, imported from Germany; later they were produced on a small scale in America. Not only were the glass fibers too large in diameter for such applications, but they were very poor electrically when subjected to moisture. The water solubility of certain constituents of these early glass fibers was so great, relatively, as actually to produce an alkaline electrolyte in the interstices within the glass mat. Also, the relatively large fibers were not only a health hazard to workmen, but were too brittle to serve properly many electrical uses. The seeming brittleness, of course, was a function of the fiber diameter to the permissible radii. The production of finer diameter fibers overcame this seeming brittleness, although other aspects of this still leave much to be desired, particularly as related to the abrasive quality or the cutting of one glass fiber by another glass fiber.

If the reader will refer back to the tabulation near the beginning of this article, showing the relative order of merit as regards water solubility, alkalinity, etc., it will be clear to him why glass for electrical purposes is now referred to as "alkali free."

MANUFACTURE OF GLASS FIBERS.

Suppose we take a trip through a modern glass fiber factory. First we start with the "rock-pile"—the constituents of glass making are brought into the plant in railroad freight cars and conveyed to one of the series of huge steel bins comprising a "batch house." From this point on, the story will be told by notes under each of the pictures, Figures 1 to 22, inclusive. These pictures were not taken by the author; they were obtained through the courtesy of the Owens-Corning Fiberglass Corporation of Toledo, Ohio.

SUMMARY.

As pointed out in some detail in Article II of this series, no inorganic stones are capable of being used alone for the majority of Naval applications. No inorganic stone either stretches or bends in the sense and to the degree which is necessary in many naval applications. If it is used in the form of fibers or sheets thin enough to stand some bending, due to the large ratio of the bending radius to the thickness or diameter of the inorganic material involved, there will be interstices. These interstices have to be filled—there just is no other way around.

The extent to which inorganic stones can be used as electrical insulation in equipment designed for naval shipboard use must, therefore, depend upon the "temperature" which the organic "filler-upper" will stand without decomposition, and also upon its "life" at some assumed maximum temperature of operation. If there is *anything,* organic or inorganic, which in, of, and by itself, is able to withstand *both fire and water* and will still *stretch or bend,* the author will appreciate learning of it in order that he might correct his philosophy.

The Navy has been testing all of the several kinds of "rocks" for many years, and its data on this subject are believed to be about as extensive as that of almost any other testing agency in the country. In fact, the data are so voluminous that there is even some question as to whether or not we can see the forest for the trees. But nearly everyone, in writing a technical article, fills it up with data—so why add more data?

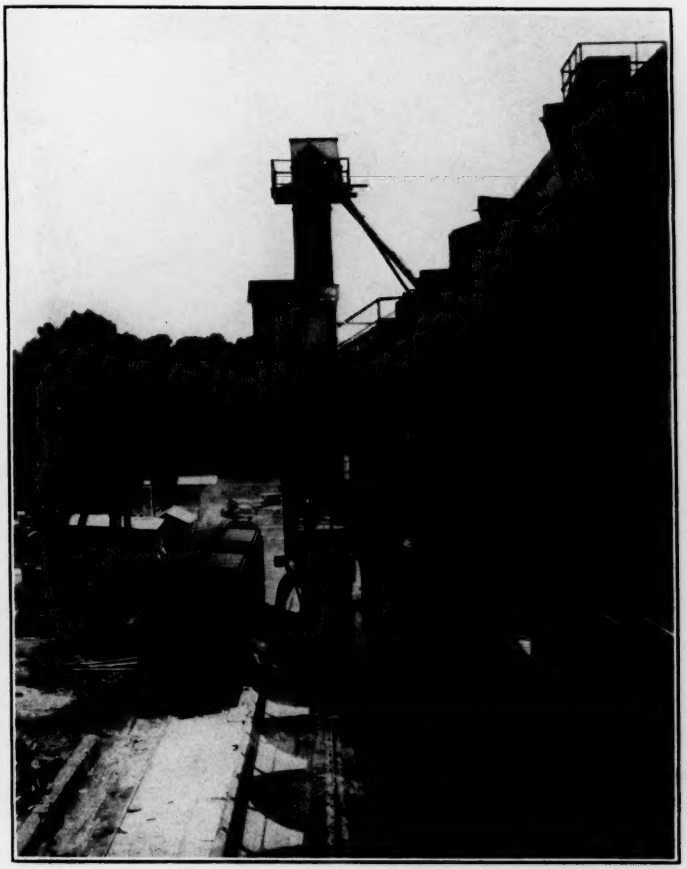


FIGURE 1.

Glass is made of sand and other minerals as outlined hereinbefore in the text—plus heat and skill. The entire process is closely controlled throughout with modern machinery, most of it especially designed for this purpose. The "rock pile" starts on its journey—first to be melted up to form glass—then to be converted into fibers. Figure 1 shows the lifting (blowing) of the raw material from the railroad freight car, by means of automatic machinery, to the appropriate steel bins comprising the batch house in much the same way as grain is handled by a grain elevator.

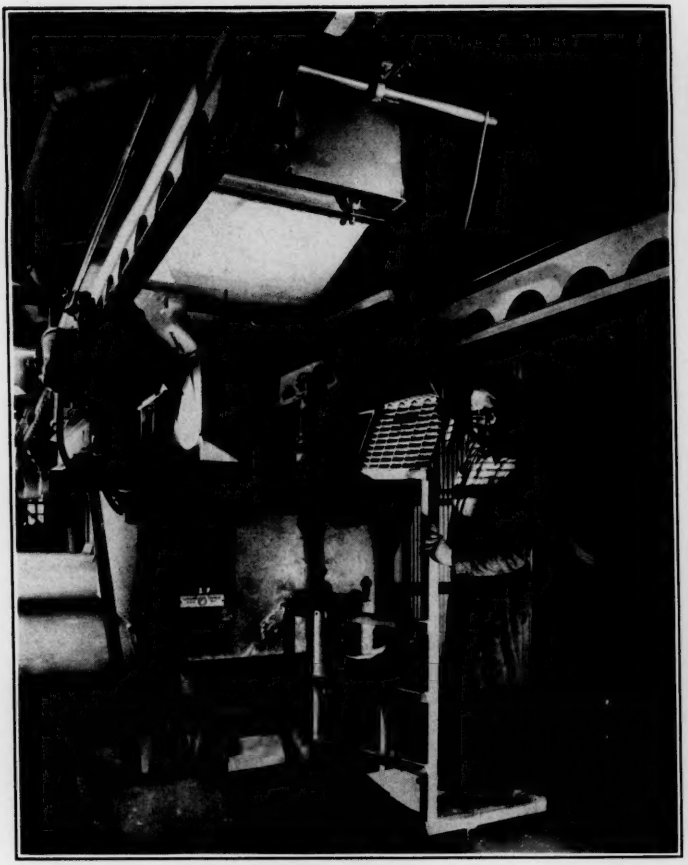


FIGURE 2.

The following is quoted from the manufacturer's description of the second step in his process:

"Beneath each storage bin is a weigh-hopper connected to an accurate recording scale. The proper amount of raw material required by precise formulas is first weighed out into the hopper and then the batch of combined materials is gathered by a collecting car running on rails beneath the bins."

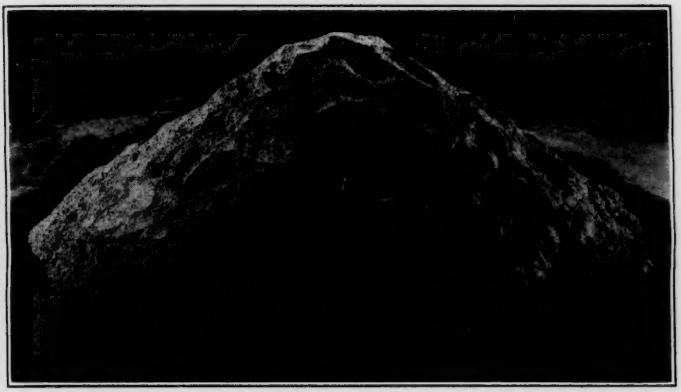


FIGURE 3.

This is what the "rock pile" looks like—this is a sample "batch." It looks like "sand" and in effect it is largely that—but it is a "controlled" rock mixture, because it will be used to make *synthetic rock*.

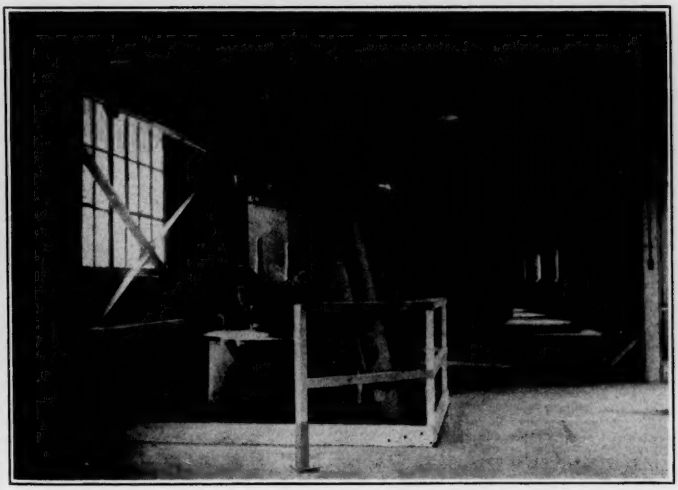


FIGURE 4.

This is the view showing a number of collected "batches," each in its huge steel can that travels on a monorail system. According to the manufacturer's description "Each step of transfer from collector to mixer to batch can is automatic and is effected through dust-tight connections."

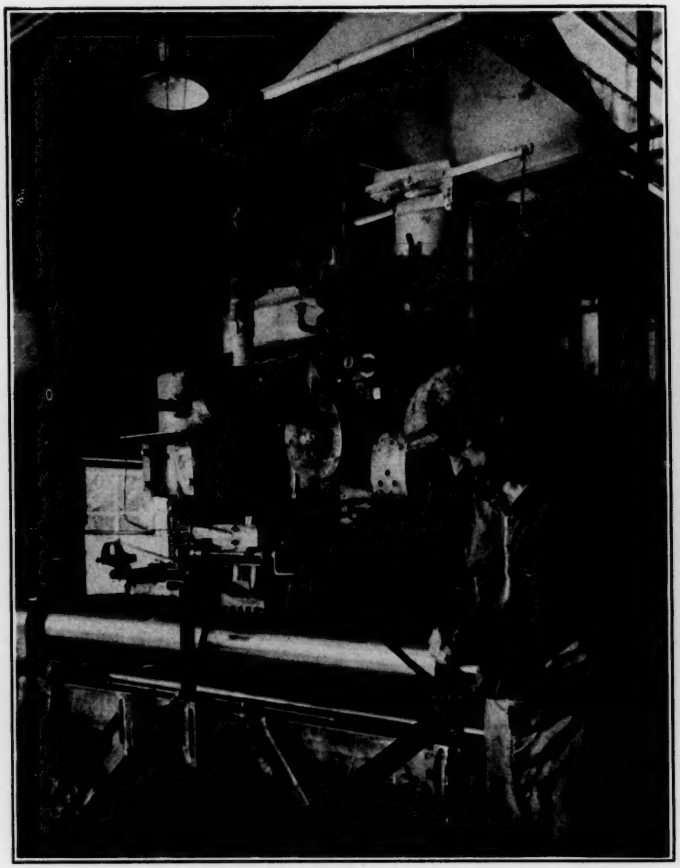


FIGURE 5.

As the batches are melted the melt runs out of a machine shown in this picture to take the form of "marbles." These marbles look just like those used in boys' games but are of a different grade, of course. It is necessary that each marble be not only of the same composition as every other marble, but that they be of the same size in order that uniformity in succeeding processes may be maintained.

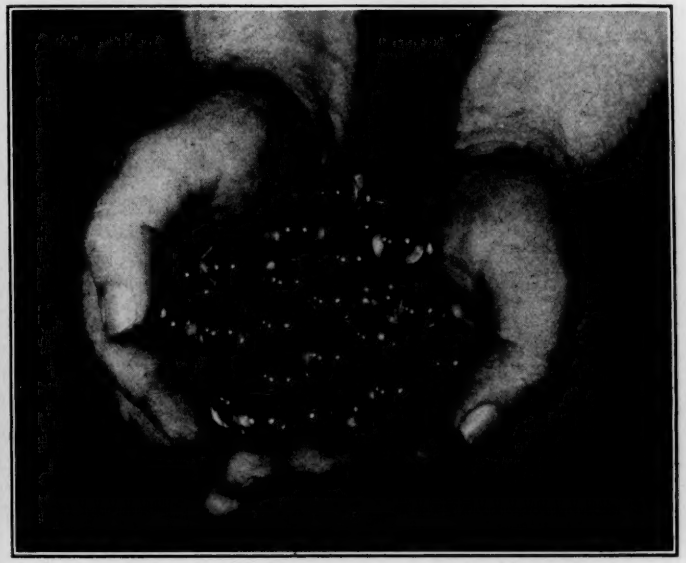


FIGURE 6.

This shows a view of the marbles produced by the machine in Figure 5. Later on these marbles will be remelted so that the molten glass may be drawn through tiny orifices to form the glass filament fibers.

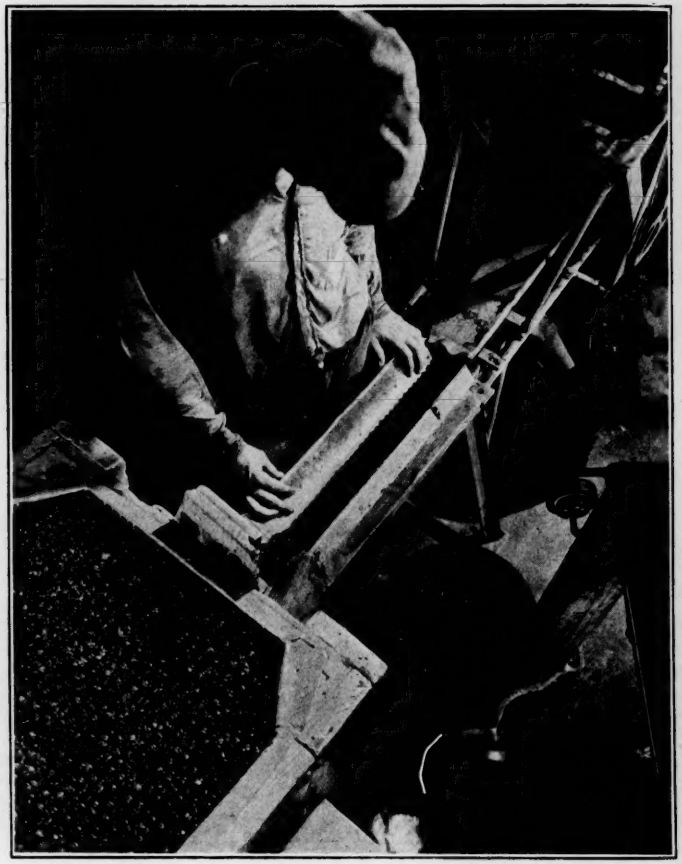


FIGURE 7.

This picture shows the careful inspection necessary to insure that all imperfect marbles are discarded. The perfect marbles, or at least those that are judged to be so, are transported to the textile glass furnaces for remelting and forming into "continuous" or "staple" glass textile fibers.

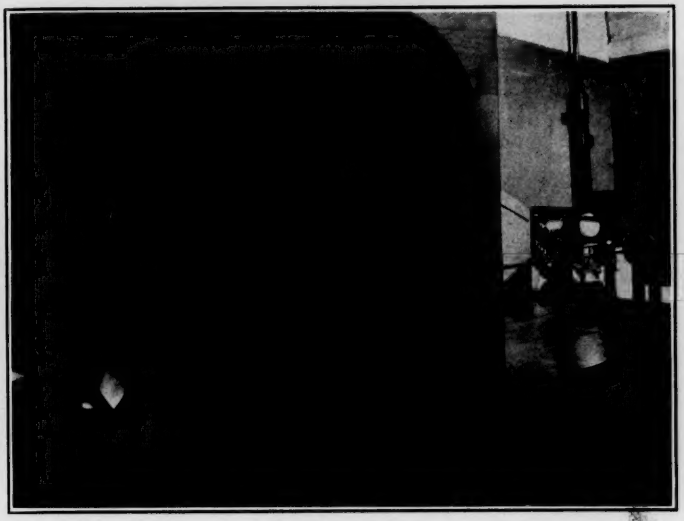


FIGURE 8.

One of these glass fibers is so small that one has difficulty in seeing it without a microscope, unless the light is just right. Even if one has eyes good enough to see it he still would not know whether or not it was uniform. According to the manufacturer's description "Here is a textile operator checking a sample of fiber for diameter uniformity, the fiber being enlarged hundreds of times for accurate inspection."

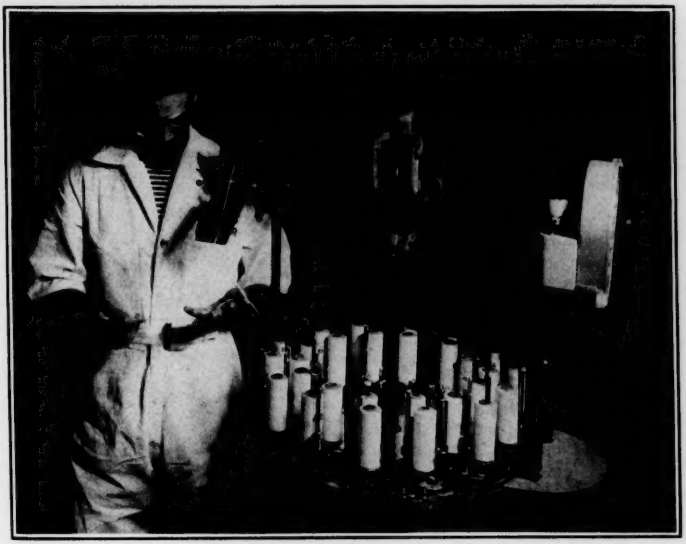


FIGURE 9.

According to the manufacturer's description "Fiber glass yarns may be fabricated into all of the customary textile forms—and on standard textile machinery. Here pure glass yarns are being made into braided sleeving, an electrical insulation material."

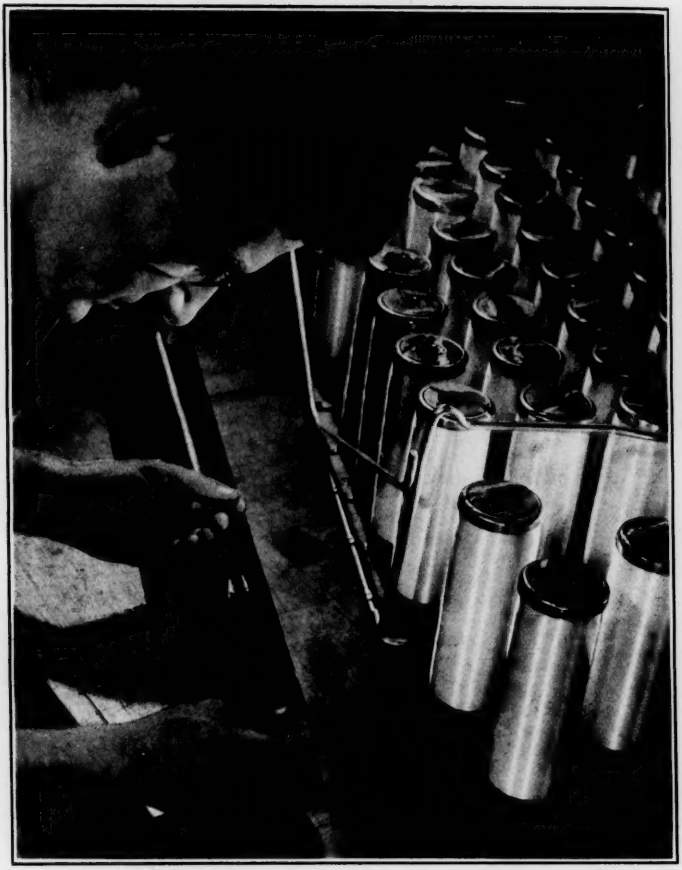


FIGURE 10.

This is another view showing the care necessary to insure uniformity. According to the manufacturer, "This quality control checker examines the twist to be found in Fiber glass yarns. Tests are made frequently to insure adherence to manufacturing specifications."

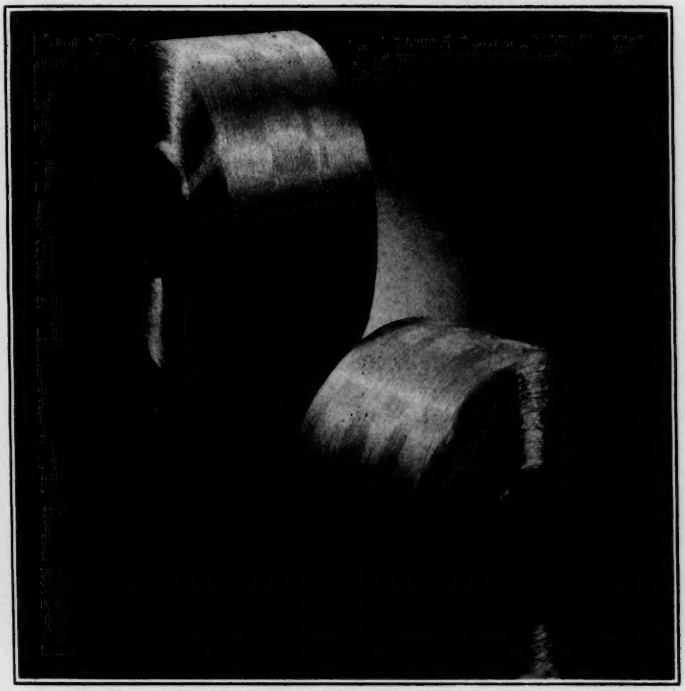


FIGURE 11.

A view of glass yarn such as is used for covering bare magnet wire. This yarn is packaged in parallel strands for the rapid covering of the wire.

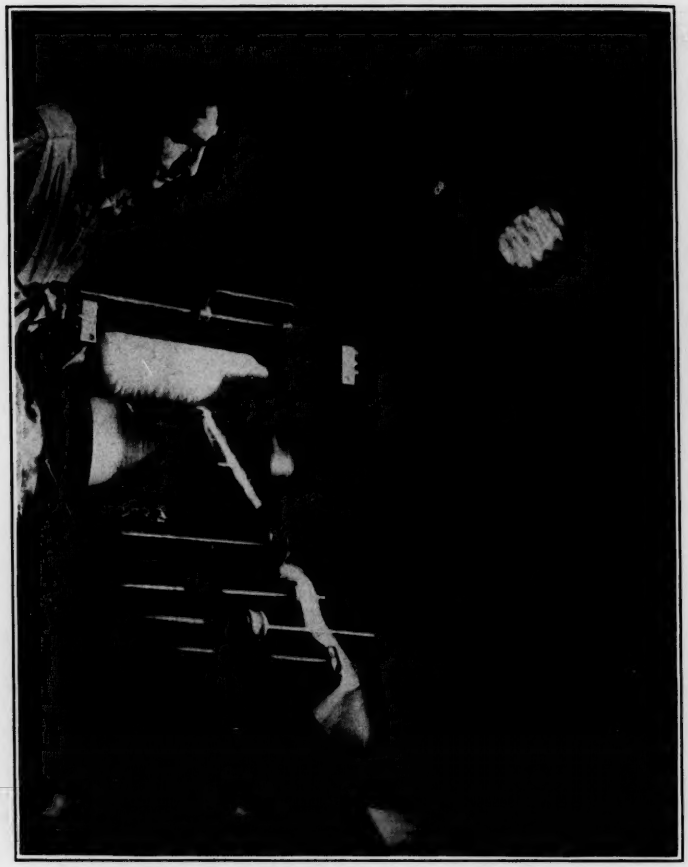


FIGURE 12.

One of the forms in which glass fiber is produced is known as "staple fiber," so-called because of the common textile term measuring a limited length. Glass "staple" fibers average 8 to 15 inches in length. "Steam drawing" is used in the production of "staple" fibers similar to that used for producing "glass wool" and other uses. According to the manufacturer, "The raw material for textile production consists of pure, refined glass 'marbles' which are melted electrically. The molten glass pours from orifices through a high-pressure steam jet, the fibers being driven downward onto a rapidly revolving drum from which they are immediately gathered into a roving and wound on a spindle spool."

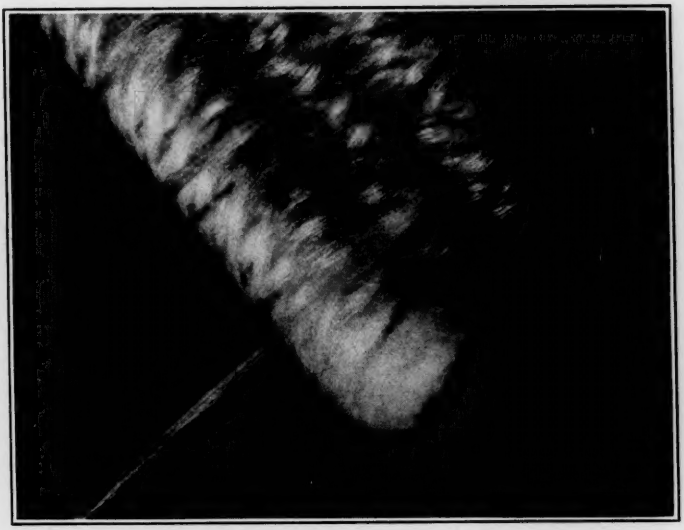


FIGURE 13.

The "staple" fiber is first packaged on tubes as a "sliver" or loose "roving." In the manufacture of staple yarns this sliver is drafted and twisted to specified forms.

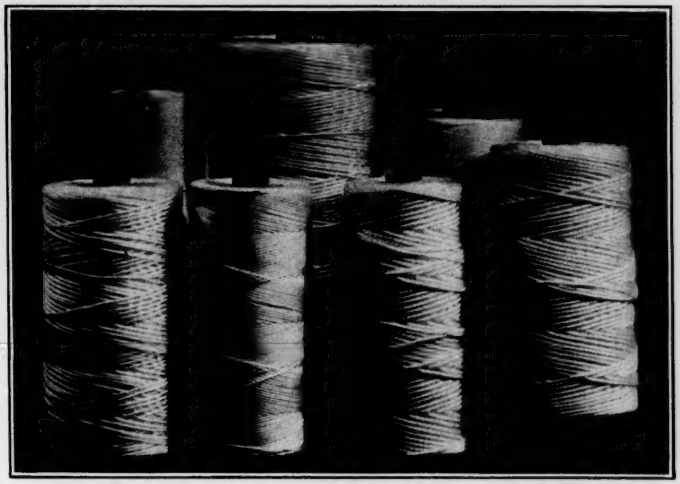


FIGURE 14.

This shows a view of the pure glass tying cords made from the yarns shown in Figure 13; and used as an electric insulating material.

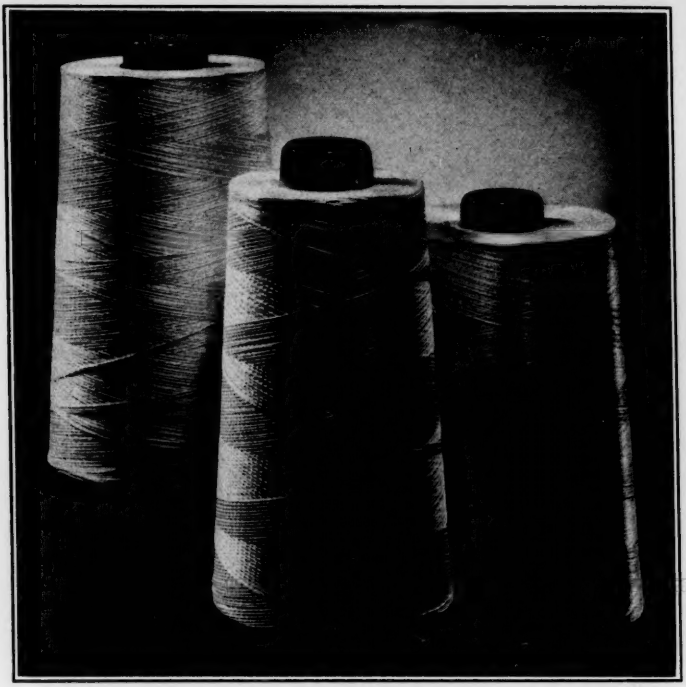


FIGURE 15.

This picture shows a different kind of glass yarn. These yarns were made from "continuous filament" fibers such as shown in Figure 11—having a much smoother, silkier appearance. These basic yarns are fabricated further to make tapes, braids, cords, and cloths.

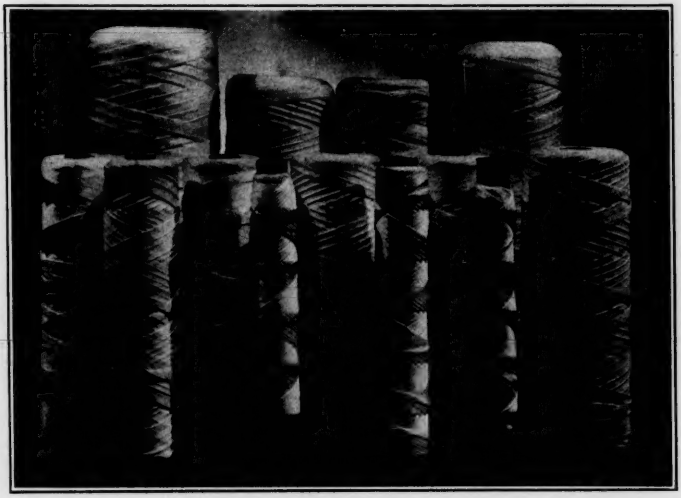


FIGURE 16.

Here is a view of some pure glass sleeving braided from the continuous type yarns shown in Figures 15 and 11. Any armature winder will know what these are used for.

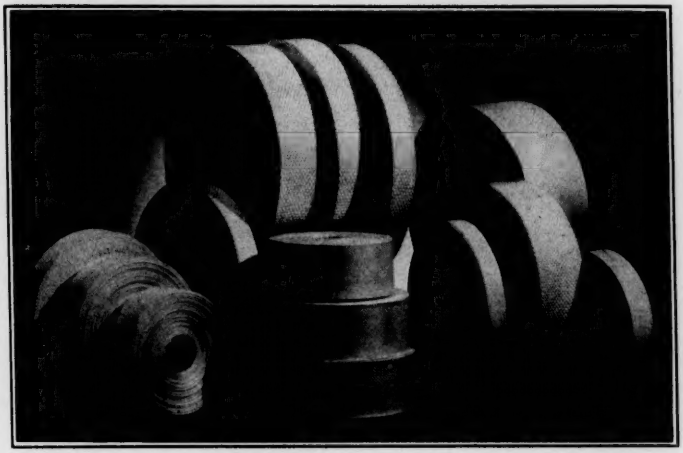


FIGURE 17.

The tapes shown in this picture are used as electrical insulation in various equipment, including certain types of cables.

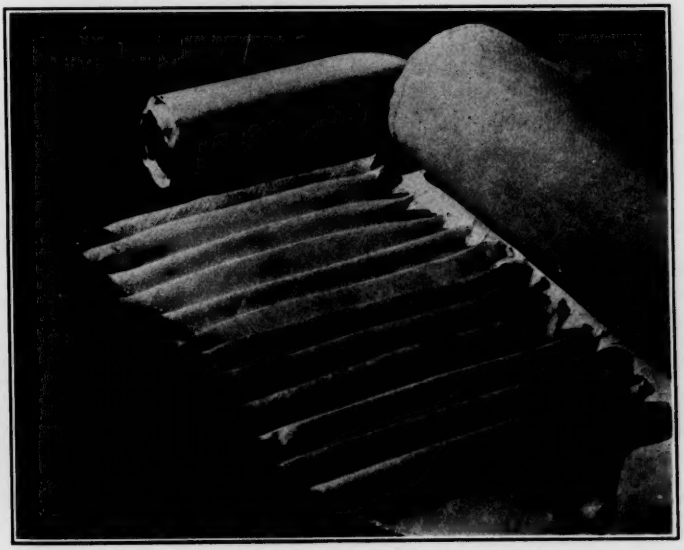


FIGURE 18.

Here are some views of representative swatches of all-glass cloths woven for use as electrical insulation.

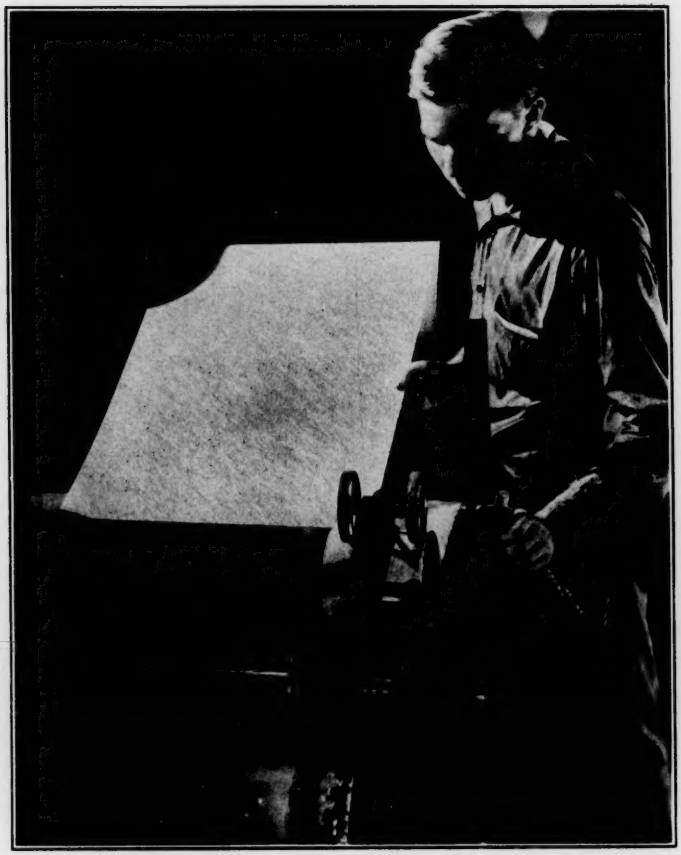


FIGURE 19.

The glass fibers produced by steam drawing are also used in products other than textiles. In the manufacture of bonded mats, the fibers are collected on a conveyor belt in jack-straw arrangement, then treated with a suitable binder. When dry, the bonded material is cut to proper size producing thin, porous sheets for use as retainer mats for storage batteries and for other applications.

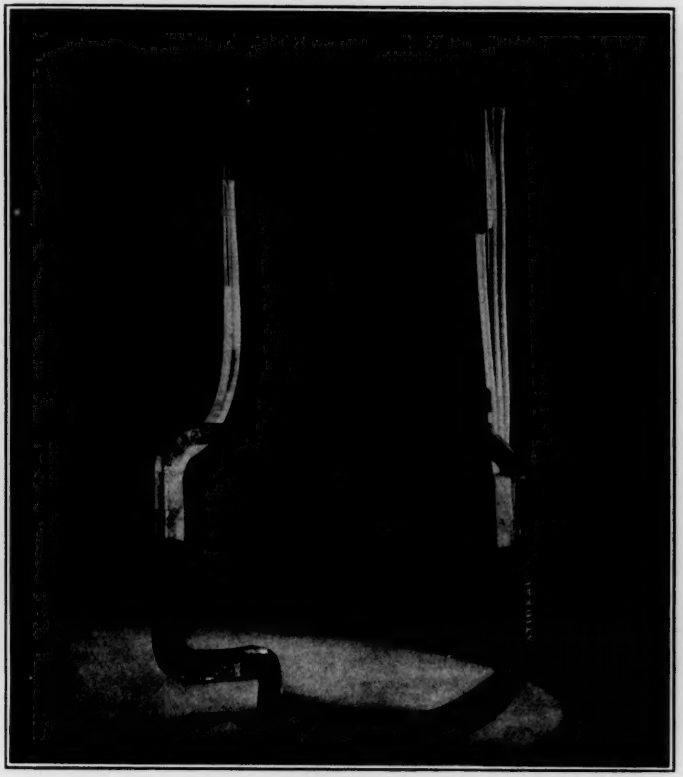


FIGURE 20.

This view shows a motor armature coil completely insulated with glass. All the magnet wire used is covered with glass yarn and then the formed coils are bound with glass tape such as shown in Figure 17. The lead wires are protected with glass braided sleeving such as shown in Figure 16.

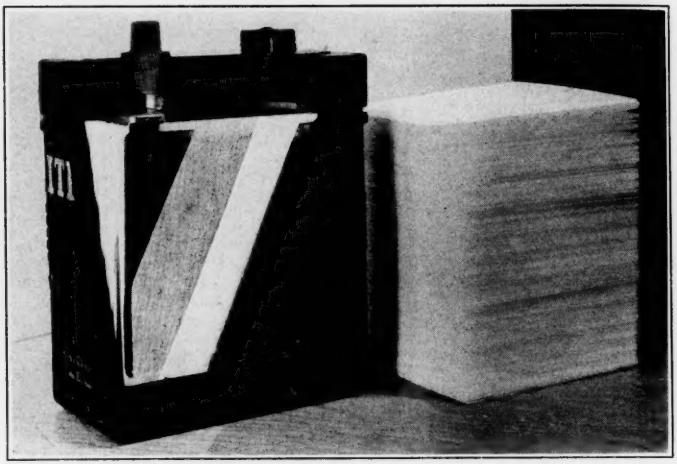


FIGURE 21.

Thin, porous mats of glass, such as shown in Figure 19, are cut to shape and used in storage batteries to retain the active material of the positive plates in position; to prevent them from "shedding" and "shorting out" at the bototm of the case.

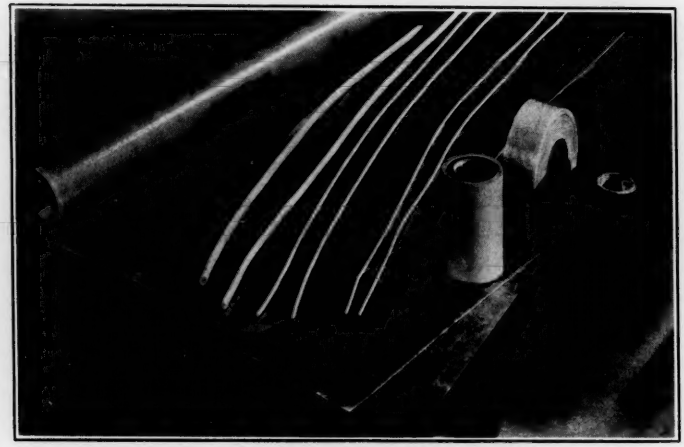


FIGURE 22.

The basic glass textile materials—cloths, tapes, tubing—are frequently impregnated with special varnishes to improve their dielectric and handling characteristics. In this illustration, there are shown various combinations of glass fiber with other insulating materials.

At some future time the author hopes to "spread a little data" too, where it might do the most good. In that event he proposes to chop down one or more of these trees in this so large a forest which is available, and to saw up some of them. If cut up right, without either "advertising" or "knocking" a particular product, they might make some valuable building lumber. But most of the lumber the author has seen published has too much of somethng to sell.

The author has something to sell too, but it is not just *one or two trees*—he wants to sell a forest—in fact, *two* of them. One forest has the *carbon* trees and the other the *silicon* trees. Both have some magnificent tree specimens among a lot of scrubs. And it takes the product of *both forests* to build our new house. If that one basic idea gets across, it is all the author expects.

In a subsequent article it is proposed to outline some points of view, particularly as to what can be done with respect to the design of *reliable, light weight electrical machinery*. That which has gone before in this and previous articles is, frankly, a build-up. The next and last one will pop a lot of questions.

TORSION OF A HOLLOW TAPERED SHAFT.

By W. E. Bleick.*

The author presents an exact solution of the problem of torsion of a hollow tapered shaft. He attains an order of accuracy hardly required for engineering purposes. The solution is presented as of possible academic interest to some members.

The torsional properties of hollow tapered shafts are treated either incorrectly or not at all in works on torsional vibration. For example, on page 34 of W. A. Tuplin's *Torsional Vibration*, New York, 1934, a formula for the spring constant of a hollow tapered shaft is derived by a method of reasoning which can be correct only for a hollow cylindrical shaft. We give here an exact treatment of the torsion of a hollow tapered shaft.

Consider a hollow shaft whose outer and inner surfaces are truncated cones, the cones not necessarily having a common vertex. Such a shaft of length l, having outer diameters D_1 and D_2, with corresponding inner diameters d_1 and d_2, is shown in Figure 1. In the following analysis it is convenient to consider a mean-diameter cone, a cone whose diameter at any section of the shaft is the mean of the diameters of the outer and inner cones. In Figure 1 it is assumed that at the vertex of the mean-diameter cone the diameters of the outer and inner cones are h and —h, respectively, where $h > 0$; i.e., the vertex of the outer cone is to the left of the vertex of the inner cone. Suppose that the shaft is made of a material having a modulus of rigidity G and is subjected to an axial moment T. If we regard the shaft as a stack of many thin hollow cylindrical slices, we may find the total angle of twist θ of the shaft by integrating the differential angle of twist $d\theta$ of each slice. The length x along the center-line of the shaft to

* Civilian Instructor, Department of Mathematics, U. S. Naval Academy.

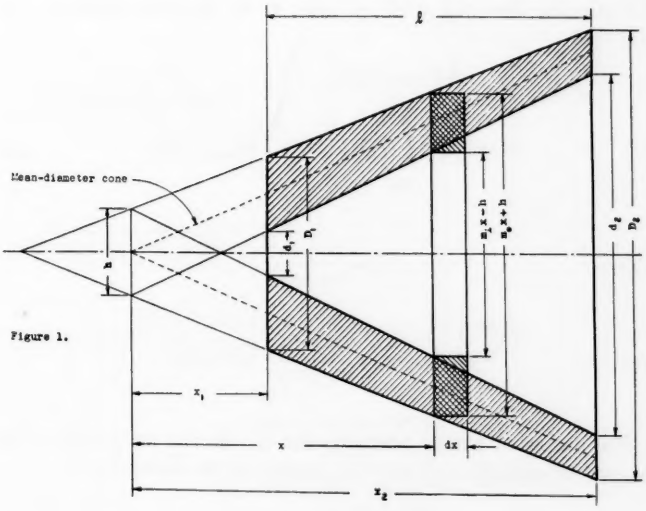


Figure 1.

a slice of thickness dx is measured from the vertex of the mean-diameter cone. The outer and inner diameters of this cylindrical slice are $m_o x + h$ and $m_i x - h$, respectively, where

$$m_o = \frac{D_2 - D_1}{l} \quad ,$$

$$m_i = \frac{d_2 - d_1}{l} \quad ,$$

and

$$h = D_1 - m_o x_1 = m_i x_1 - d_1 \quad .$$

The differential angle of twist $d\theta$ of this slice is directly proportional to the twisting moment and to the thickness of the slice, and is inversely proportional to the polar second moment of area of the slice and to the modulus of rigidity; so we may write

$$d\Theta = \frac{T\,dx}{\frac{\pi}{32}\left[(m_o x + h)^4 - (m_i x - h)^4\right] G} \quad . \qquad (1)$$

To calculate the total angle of twist θ, we integrate equation (1) and find

$$\Theta = \frac{32T}{\pi G}\int_{x_1}^{x_2} \frac{dx}{(m_o x+h)^4-(m_i x-h)^4} \quad , \tag{2}$$

where $$x_1=\frac{D_1+d_1}{m_o+m_i} \quad ,$$

and $$x_2=\frac{D_2+d_2}{m_o+m_i} = x_1+1 \quad .$$

The theory of partial fractions shows that the integrand of the integral in equation (2) may be written in the form

$$\frac{1}{(m_o x+h)^4-(m_i x-h)^4} = \frac{1}{4h^3(m_o+m_i)^3}$$

$$\left\{ \frac{(m_o+m_i)^2}{x} - \frac{(m_o-m_i)^3}{(m_o-m_i)x+2h}\right.$$

$$-4m_o m_i \frac{(m_o^2+m_i^2)x+h(m_o-m_i)}{(m_o^2+m_i^2)x^2+2h(m_o-m_i)x+2h^2}$$

$$\left. - \frac{2}{h(m_o+m_i)} \cdot \frac{(m_o^4-m_i^4)}{1+\left[\frac{(m_o^2+m_i^2)x+h(m_o-m_i)}{h(m_o+m_i)}\right]^2} \right\} . \tag{3}$$

Equation (3) is most easily verified by showing that the sum of four fractions of the right member is equal to the left member.

After substituting equation (3) into equation (2), and making use of the properties of differentials, we find

$$\Theta = \frac{8T}{\pi G h^3 (m_o+m_i)^3} \int_{x_1}^{x_2} \left\{ \frac{(m_o+m_i)^2 dx}{x} - (m_o-m_i)^2 \right.$$

$$\frac{d[(m_o-m_i)x+2h]}{(m_o-m_i)x+2h}$$

$$-2m_o m_i \frac{d[(m_o^2+m_i^2)x^2+2h(m_o-m_i)x+2h^2]}{(m_o^2+m_i^2)x^2+2h(m_o-m_i)x+2h^2}$$

$$\left. -2(m_o^2-m_i^2) \frac{d\left[\frac{(m_o^2+m_i^2)x+h(m_o-m_i)}{h(m_o+m_i)}\right]}{1+\left[\frac{(m_o^2+m_i^2)x+h(m_o-m_i)}{h(m_o+m_i)}\right]^2} \right\}, \qquad (4)$$

or, upon integrating,

$$\Theta = \frac{8T}{\pi G h^3 (m_o+m_i)^3} \left[(m_o+m_i)^2 \log_e x - (m_o-m_i)^2 \log_e \right.$$

$$[(m_o-m_i)x+2h]$$

$$-2m_o m_i \log_e [(m_o^2+m_i^2)x^2+2h(m_o-m_i)x+2h^2]$$

$$\left. -2(m_o^2-m_i^2) \arctan \frac{(m_o^2+m_i^2)x+h(m_o-m_i)}{h(m_o+m_i)} \right]_{x_1}^{x_2}. \qquad (5)$$

Equation (5) has been derived on the assumption that $h > O$. Equation (5) is still valid, however, if $h < O$, a case which is illustrated in Figure 2. If $h = O$ it is simpler to abandon equation (5) and make a fresh start. In the case $h = O$ equation (2) reduces to

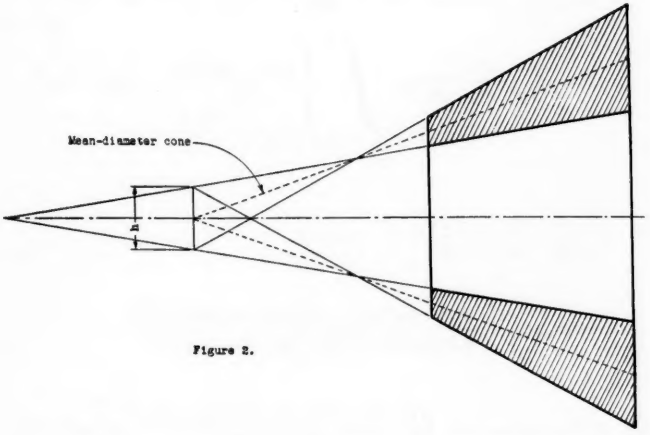


Figure 2.

$$\Theta = \frac{32T}{\pi G}\int_{x_i}^{x_2} \frac{dx}{(m_o^4 - m_i^4)x^4}$$

$$= \frac{32T}{3\pi G(m_o^4 - m_i^4)}\left[\frac{1}{x_1^3} - \frac{1}{x_2^3}\right] . \qquad (6)$$

In addition to the angle of twist θ of a hollow tapered shaft, the values of the equivalent length L and of the torsional spring constant k may be required. These may be computed by means of the relations

$$L = \frac{\pi G\Theta}{32T} \qquad (7)$$

and

$$k = \frac{\pi G}{32L} . \qquad (8)$$

The equivalent length is the length of a solid cylindrical shaft of unit diameter having the same torsional spring constant as the hollowed tapered shaft.

DISCUSSION OF ARTICLE: CONTROLLABLE PITCH PROPELLER, BY J. H. STRANDELL, PUBLISHED IN THE JOURNAL FOR AUGUST, 1940, VOL. 52, NO. 3, PAGES 408-448.

The article, "Controllable Pitch Propeller," published in the August JOURNAL *has elicited adverse criticism. Due to circumstances, the article was published without reference to any members of the Council. The Secretary-Treasurer, as Editor, accepts full responsibility for the publication of the article.*

Aside from the merits of the article itself, the opportunity it has offered for the presentation of the following discussion must be accepted with thanks.

The author of the original article has been given copies of each of the discussions and is preparing an answer. His discussion cannot be made ready for this issue and will appear in February, 1941.

Discussion, Lt. Commander Pleasant D. Gold, Jr., U. S. N., Member.

The subject of the controllable pitch propeller is always of interest to the marine engineer, and more than usually so at present, as considerable interest is being shown both in Europe and in the United States toward the application of these propellers. The Navy Department has been investigating, during the past few years, various methods of control and various types of propeller mechanisms. Mr. Strandell's article is therefore of especial interest at this time. The author not only emphasized the advantages of a controllable pitch propeller, but reviewed the history of the Kaplan mechanism as applied to turbines as well as to ship's propulsion, and described other mechanisms for controlling the pitch of propellers. He finally described a method proposed by him for submarine application.

The controllable pitch propeller has been one of the chosen topics of inventors. Numerous types of both propeller and control have been submitted to the Navy Department, among them was the type proposed by the author. Many of those submitted have been well designed and entirely practical. However, there is a tendency to exaggerate the problem, resulting in designs more complicated than is required.

John Bourne stated, in his classical book on the screw propeller, published in 1867, "In ordinary screw vessels there does not appear to be much advantage derivable from varying the pitch of the screw or the angle of the propeller blades, for screw engines will go at nearly the same speed whether the wind be adverse or favorable or whether the vessel is much or little immersed. This, indeed, is one of the defects of the screw as heretofore applied and the use of an expedient for changing the pitch involves the supposition that in adverse winds, or with deep immersions, the velocity of rotation of the screw is very much diminished, which,

however, is not the case. Nor is the expedient more remarkable for its novelty than for its advantage. Hooke, in the windmill instrument he showed to the Royal Society in 1683, had an arrangement for altering at pleasure the angle of the blades; and Millington, in his patent of 1816, states that the vanes or propelling blades he employs are: 'to shift on their pivots, or points of attachment, so as to alter the angle which they make with the plane of their motion, from 45 degrees to any greater or lesser angle, according to the speed with which they are moved.'" In spite of the many advances in the art of screw propellers, these statements have not been successfully contradicted. The advantages of the screw propeller are dependent upon its application, and had Bourne interested himself with vessels used for towing, or had he problems of the backing turbine or the Diesel engine in torsional critical ranges, he would have appreciated the advantages of pitch control. He did, however, recognize the erroneous conceptions of his time and the limitations of the device. The same misconceptions exist in the minds of many at the present time. There are sufficient actual advantages to pitch control to warrant its use for many specific problems. It is believed that exaggeration of these advantages will lead to ill-advised applications which will be harmful to the future of the mechanism.

Fortunately, the resistance characteristics of a ship's hull and the thrust characteristics of a propeller follow similar physical laws. Throughout the range of speeds of a conventionally constructed vessel the slip of the propeller varies over narrow limits. If the propeller be properly designed the propeller efficiency will be close to the maximum throughout the range of speeds of the ship. The efficiency curve shown in Figure 1 is that of a recent naval vessel. The slip curve is obtained from model tests of this vessel. It will be observed that the true slip is 15.7 per cent at ten knots while the true slip at thirty-four knots is 22 per cent. The test was not continued below ten knots due to the limitations of the test apparatus. The efficiency curve shows that a maximum efficiency of 69.4 could be obtained, while the efficiency at 15.7 per cent slip is 69.3 and at 22 per cent slip is 67.5. Any advantage in efficiency which could be gained by remaining at exactly the optimum pitch would be lost due to the less efficient controllable pitch propeller.

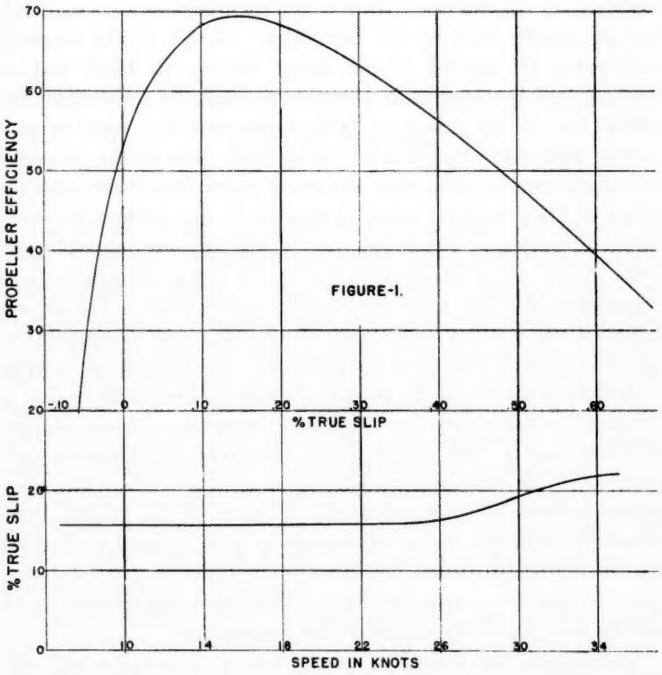


Figure 2 was constructed from tests conducted on a tug having a controllable pitch propeller. The tug was without tow. The propeller was designed for best efficiency under this condition. It will be noted that the best pitch setting is practically the same for every speed. The RPM. curves have been included to indicate the effect of maintaining a constant RPM. Unfortunately neither the SHP. nor the mechanical efficiency is available at the present time. The BHP. was obtained from stack temperatures. Inasmuch as the order of accuracy is unknown the numerical values have been omitted.

The propeller of minimum loss is the object of most designs. Past experience indicates that propellers having small hubs, and nearly constant virtual pitch, results in the nearest approach to this objective. The controlled pitch propeller has, in practically all

FROM TESTS CONDUCTED ON SMALL TUG
HAVING CONTROLLABLE PITCH PROPELLER.
(WITHOUT TOW)

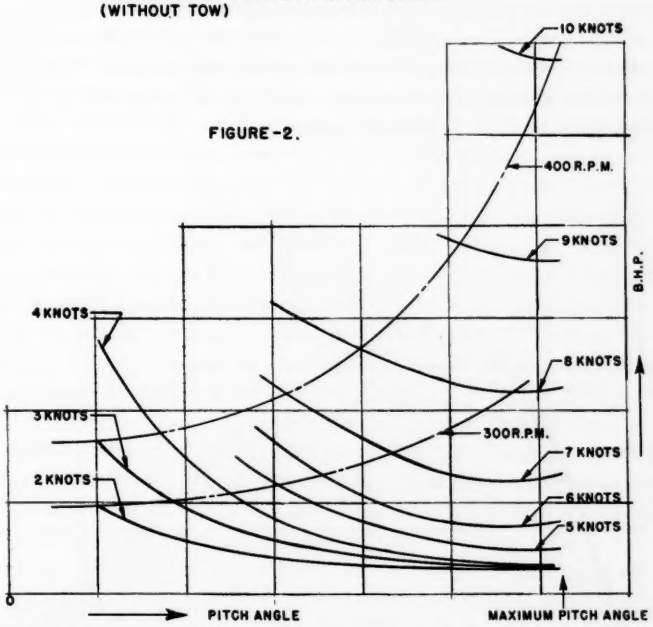


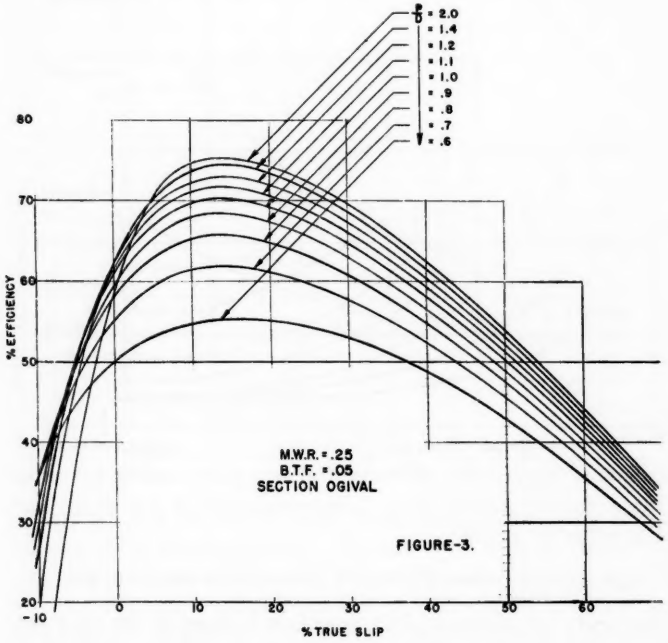
FIGURE-2.

designs, a larger hub, and except at one pitch setting has other than a constant virtual pitch. The pitch angle of a constant face pitch propeller equals:

$$\text{arc tan } \frac{P}{2\pi R} \text{ where P} = \text{pitch in feet, R} = \text{radius in feet.}$$

This angle for constant pitch propellers is large at the root sections and relatively small at the tip sections. To turn this blade through any angle, therefore will affect the pitch of the tip sections much more than the other sections. The effect of decreasing the pitch of a propeller designed for a constant pitch at the normal setting is to unload the tip sections. Further decrease in pitch brings the tip sections into a negative slip position, while the root sections remain in the ahead position. The tip sections only will therefore be used in backing while the root sections may remain in an ahead driving position.

The efficiency of the propeller is not only detrimentally affected by this variation in pitch due to the distortion of the blade, but also due to the fact that the efficiency of high pitch ratio propellers is inherently superior to those of low pitch ratio. Figure 3 shows the results of a series of tests of model propellers of constant diameter but of different pitch.



As suggested above, the controllable pitch propeller has many inherent advantages and it is therefore unnecessary to manufacture additional advantages in order to plead its cause. In the first three paragraphs of the article under discussion, the author expresses a number of different ideas. These ideas, it is believed, are held by many marine engineers who normally would accept no unverified statements concerning the mechanisms used on board ships. Inasmuch as it is considered important to correct the im-

pressions which may have been created by these paragraphs, they will be considered in more detail than would otherwise be justified.

First, "With a fixed pitch propeller on a ship, only one operating function can be efficiently and completely satisfied. This is usually selected for rated speed of the ship and full horsepower developed by the engines with the ship's displacement in the loaded condition, in calm water and no wind." Please refer to Figure 1 and it will be noted that the fixed pitch propeller satisfies quite well all of the ahead conditions. Again quote, "It becomes apparent that when a ship is operating with a fixed pitch propeller any condition other than the one that the propeller is designed for will not utilize the engine power to its full extent. Head or tail winds will increase or decrease the resistance of the ship with consequent variation in RPM. of the engine due to the alteration of the propeller torque." Inasmuch as the power varies approximately as the cube of the RPM., appreciable changes in power cause relatively small changes in RPM. Therefore, while what the author has said is true, it becomes important only when the variation in effective resistance is large.

Again quote: "If the propeller is designed for maximum efficiency at full speed of the ship, obviously the angle of attack at all speeds below full speed will be greater than that for maximum efficiency at these lower speeds." This statement is not correct. The angle of attack is a direct function of the propeller slip. It is seen in Figure 1 that the slip normally decreases, if it changes at all, as the speed is reduced. (This is not always true. Certain high speed planing boats have such relatively high resistance below planing speeds that the propeller slip decreases as speed increases.)

Again quote: "If now the condition is to accelerate the ship from zero speed to full speed, the propeller at no point below full ship speed reaches its theoretical RPM. because this fixed angle of attack is greater than the most efficient at all speeds of advance below full speed of the ship. In other words, in all the above-mentioned cases there are losses of power, which means that the available engine power cannot be utilized in many instances of operation, when it is connected to a fixed pitch propeller." The

resistance of a ship at low speeds is fortunately low and, while the thrust of a low pitch ratio propeller is greater at the high slips occurring during acceleration, the actual gain in time to attain full speed from stop is not greatly affected. When the author refers to "losses of power" it is believed that he has reefrence to the inability of the engine to produce full power at low RPM., a limitation due to lack of available power rather than an actual power loss resulting from low propeller efficiency.

Again quote: "As the conditions under which an airplane is working with a fixed pitch propeller are in many respects very similar to the conditions under which a ship is functioning, an airplane provided with a fixed pitch propeller has only one flight function that can be efficiently satisfied. This may be selected as maximum speed with the engine under wideopen throttle condition. Then, all other conditions such as take-off, climb, ceiling, and cruising speed at altitude, and low altitude performance cannot be satisfied with the fixed pitch propeller. The aeronautical engineers found it an absolute necessity to develop the controllable pitch propeller because of the need for better airplane performance. The improvement has been shown to be so great as to well pay for the added complication and expense involved." The range of conditions under which an airplane must work are very different from the conditions under which a ship functions. The airplane must be able to take off under full load, must be able to climb efficiently, and cruise at different altitudes efficiently. The ship's propeller uses water of practically constant density as a medium for propulsion and the ship has relatively little difficulty in accelerating. The comparison of the airplane and the ship is irrelevant and such comparison leads to erroneous conclusions.

Again quote: "The speed of ships has greatly increased in the last few decades and as a consequence large expensive power plants must be installed. Obviously, it is of paramount importance that the power plants be fully utilized for better ship's performance and it is believed that one of the greatest contributions to that effect is the installation of a controllable pitch propeller." The author is guilty here of "wishful thinking."

Again quote: "Possibilities of improvement in ship's performance in connection with a controllable pitch propeller are even

more promising when it is realized that the reversing element of the power plant is not needed, thus making a greatly simplified machinery plant and reducing the time of reversing or changing the speed of the ship." The author here lists an actual advantage of the controllable pitch propeller. Instead of a reversing turbine, a reversing gear, or a reversible electric motor, a reversing mechanism in the propeller is substituted. That this substitution actually increases simplicity or reduces the time of reversal or of changing the speed of the ship will depend upon the propeller design and the size and power of the control mechanism. The propulsive efficiency under normal operating conditions will be adversely affected. This will be especially true for high speed vessels. Prior to arbitrarily deciding upon the installation of a controllable pitch propeller as a substitute for other reversing mechanisms, consideration should be given to the other methods of stopping and backing the ship.

Mechanically there is no real difficulty in designing, manufacturing and maintaining the controllable pitch propeller. The author's statement that "For changing the pitch, large forces are required, even greater than the propeller thrust itself," is only true at low speeds where the thrust of the propeller is small, or where insufficient care has been taken in blade section design to insure low twisting moments about the blade axis, or in hub design to insure low friction losses in the control apparatus.

The author suggests the question, "Why the controllable pitch propeller has not, until very recently, been extended to use in large ships?" He answers this question "first, the imperfections of those early designs mentioned above and the tendency of men devoting themselves to a highly specialized art to become reluctant to try anything which deviates from the conventional and generally approved design." Controllable pitch propellers were properly in use during the last century when sail was combined with steam, in order that, when under sail with favorable winds, the propeller pitch could be increased to obtain thrust from the propellers without exceeding the limiting revolutions of the engines. Controllable pitch propellers were also properly used by trawlers engaged in an occupation requiring accurate control of speed at the low speeds required for trawling. Propellers of this type have

been valuable for special applications, in order to correct for large variations in effective resistance or to correct for the limitation of the propulsive machinery. For the conventional hull, under usual circumstances, the use of a constant pitch propeller results in a better efficiency at all speeds. This fact, rather than the reasons given by the author, probably account for the reluctance of the propeller designer to accept the controllable pitch propeller for large ships.

The article includes the history of the Kaplan turbine. Kaplan perceived that a mechanism similar to that used on ships for controlling the pitch of a propeller was applicable to water turbines and pumps. This was theoretically correct, and proved to be an excellent application. The success of the mechanism for hydraulic turbine application is undisputed; however, the fact that this history finds itself in an article on the controllable pitch propeller may lead to the inference that the problems are identical. The turbine problem and the pump problem are similar, if constant RPM. is required. In which case, to obtain good efficiencies, there should be a definite relation between water velocity and blade setting. The ship's propeller, fortunately is not required to operate at constant RPM. For the effect of such a limitation, please refer again to Figure 2. The water turbine application, like the airplane application, has no bearing upon the subject of this article. Figure 4 of the subject article shows the efficiency of a water turbine. Attention is invited to the fact that the methods for determining and comparing efficiencies of marine propellers is different from that of turbines and pumps, and therefore the efficiency curve in Figure 4 cannot be directly compared with the propeller efficiency curves included in this discussion. If the kinetic energy contained in the propeller's slip stream were not charged against the propeller, the propeller efficiency would compare favorably with recorded efficiencies of turbines and pumps.

The sections of the article devoted to the various mechanisms illustrates interesting methods for controlling pitch. In the files of the patent office may be found many more. There is therefore no apparent object to be gained by discussing these methods, except to invite attention to the statement the author makes relative to the design proposed by him, quote: "The working principle of

the mechanism as shown in Figure 20 is believed to be the simplest possible." The author has substituted for the servo-motor, control, and oil pump of the previous mechanism described by him, an electric motor with control ring, gear sprocket, and gear train, a speed reducer which he terms a torque converter, and an elongated screw and nut which he terms a power-jack. The object of all this equipment is to move the inner shaft back and forth. Simplicity and reliability are comparative terms, but the use of the expression by the author, "simplest possible," is, I believe, subject to question.

Under the section headed "What advantages has the controllable pitch propeller for submarine and other ships?" the author discusses the available power for charging batteries on a submarine with engine directly connected to the propeller, or connected by a reduction gear. The point is well taken, and under the assumed conditions it is possible to charge the batteries at a greater rate, as is shown in Figure 28. The total amount of power available for charging being "A" for the fixed pitch propeller and "B" for the controllable pitch propeller, assuming the maximum RPM. is maintained. Attention is invited to the increase in SHP. required to maintain the speed of "thirty knots" for the "submarine" if the controllable pitch propeller is used at the maximum RPM. The words "excess power" should be changed to "available power" to prevent the impression that the fixed pitch propeller requires more power to accomplish its mission, which is to propel the ship. The limitation of MEP. of the Diesel engine reduces the power available for changing batteries at the reduced RPM's.

In the same paragraph that the author explains the advantages of the controllable pitch propellers for increasing the charging rate of a submarine, by presenting the performance curves of a 40-knot ship, he also presents an RPM., BHP., fuel consumption curve of a 4-cycle Diesel engine, which he suggests be superimposed on the other chart. Neglecting the order of the SHP. scale, it will be noted that by the proper gear ratio it would be possible to cause the $\left(\frac{H}{D} = 1.2\right)$ curve to pass through the major axes

of the ellipses. The variation of power with RPM. required to drive a ship is therefore fortunate for the Diesel engine as well as for the propeller. (H = the European symbol for pitch.)

In summation of the advantages of the controllable pitch propeller for submarines the author mentions the limiting minimum speed of the Diesel engine as another reason for the controllable pitch propeller, stating that " with a Diesel engine connected to a fixed propeller the speed of the ship can be reduced to only one-third or at most to one-fourth of the maximum speed." When it is realized that this condition represents approximately two to four per cent maximum power, it is recognized why it is difficult to obtain a Diesel engine governor capable of bettering this minimum speed. However, since the power is so low it may be better to either run on the motors or charge the batteries during this time rather than install a propeller control mechanism for the purposes.

The last section, entitled " Propeller Manufacture," is devoted, with the exception of the first paragraph, to examples of the benefits of the controllable pitch propeller on a towboat and a freighter. While the author does not so state, the curves in this section refer again to " available " power and unless this is recognized these curves may be misleading.

A discussion, such as the above, may lead to the impression that this writer is inclined to a prejudice against the mechanism under examination. This, however, is not true, as evidenced by the investigations now being conducted by the Bureau of Ships. It is believed, however, that one misapplication may lead to prejudice on the part of many. It is considered therefore to be important that such misapplications be avoided. Pertinent to this, the records of the Bureau include the history of the United States Submarine *Thrasher,* equipped in 1912 with a poor engine, and a satisfactory controllable pitch propeller. Due to the condition of the engine, both engine and controllable pitch propeller were removed. We have had no controllable pitch propellers on submarines since. It is probable that the failure of this engine led to the belief that part, at least, of the fault lay with the propeller.

Were it possible to design a propeller having adjustable diameter as well as pitch, and were it used on a conventional hull during

normal operation, and designed to remain at all times at the position of optimum efficiency, the diameter and the pitch would change but a small amount, and the percentage increase in efficiency over that of a fixed pitch propeller would be likewise small. The controllable pitch propeller is therefore a device for unusual usage and, as before stated, to correct radical changes in the effective resistance of the ship, or to correct for deficiencies of the propelling plant. In many cases, it is believed that these deficiencies can better be corrected by other means than by the use of a controllable pitch propeller.

Quoting again John Bourne's opinion of 1867: "In ordinary screw vessels there does not appear to be much advantage derivable from varying the pitch of the screw."

Discussion, Captain Lybrand Smith, U. S. N., Member.

Mr. Strandell's paper may be divided roughly into two parts, although these parts are more or less scrambled together throughout the paper. One part is the recommendation of specific mechanisms for controllable pitch propellers. The other part sets forth the theories Mr. Strandell has adopted regarding propellers, in order to back up his advocacy of controllable pitch propellers.

There need not be much discussion of the specific mechanisms he proposes. His data regarding the mechanisms in the hub for moving the blades and in the hull for controlling this movement are drawn almost entirely from advertisements and advertising literature. For our present purposes we may accept these advertising assertions at face value, and agree that when and if we want a controllable pitch propeller, Mr. Strandell has described good mechanisms, although we need not agree that he has described the best.

The reliability of any such mechanisms must be considered. His advertisements assert the proposed mechanisms are reliable. But an assertion that any mechanism whatsoever inside the hub of a propeller, reach rods inside the shaft, and control mechanism outside the shaft could be as reliable as a solid propeller on the end of a simple shaft would be merely silly.

Any controllable pitch propeller is of fundamental necessity less reliable than a solid propeller. In the case of small unimportant craft, this relative unreliability may be tolerated, because their sterns may be hoisted out of water for inspection and overhaul at such intervals as desired. But the relative unreliability would be intolerable in the case of large combatant ships which may be out of dry dock as much as a year.

It would be impracticable to inspect and overhaul the hub mechanism by divers. It is hard enough to do routine overhaul

on a solid propeller of a large ship while diving in the murky waters of a harbor tideway. I know. I have done it.

The citation of Kaplan turbines much bigger than battleship propellers is not a case in point. They can be inspected any time they are stopped. One merely goes inside the tunnel, or "guide case," and walks around on the blades. I know. I have done that, too.

The comparison of a water turbine with a propeller is an oversimplified ruse which is fashionable in certain quarters. It is true you could put a Kaplan turbine wheel on a ship's shaft and a ship's propeller in place of the Kaplan turbine, and both would work—inefficiently. However, they are so different in degree that they are almost different in kind. The comparison is almost as bad as comparing your automobile engine with your mechanical refrigerator, just because they are both heat machines running in reverse senses, and both operate according to the laws of thermodynamics.

A ship's propeller and a Kaplan turbine are both hydraulic machines running in reverse senses, and both operate according to the laws of hydrodynamics. It is up to the designer to apply these laws to get the best results for the two different applications.

There are criticisms of those parts of Mr. Strandell's paper which deal with the mechanisms, but none of these criticisms implies fool ideas. When we come to his propeller theories, the case is different. It is difficult to find a single theory expressed by him which is not fallacious.

To take up Mr. Strandell's fallacies one by one would require an excessively long discussion. It seems preferable to review a few fundamentals of propeller design which the reader may apply to many cases; and then point out a few of the principal absurdities in Mr. Strandell's paper.

There are a number of good methods of propeller design. One of the best is the Taylor method (1).* It is thoroughly founded on experimental observations, and thoroughly proved by successful ships. Any method giving radically different results is wrong.

* Number in parentheses refer to bibliography at the end of this discussion.

For these reasons, and because the Taylor method is readily available to American shipbuilders, it will be used to illustrate the fundamentals.

Taylor shows (2) that one of the most useful ways of plotting propeller information for design work is to plot it against a certain Basic Coefficient, denoted by B, which is:—

$$B = \frac{(\text{Revolutions}) \times (\text{Power})^{0.5}}{(\text{Speed})^{2.5}}$$

"This is not technically 'dimensionless.' For a technically dimensionless coefficient we should, if ρ denote density of the fluid in which the propeller works, use—

$$\frac{(\text{Revolutions}) \times (\text{Power})^{0.5}}{\rho^{0.5} \times (\text{Speed})^{2.5}}$$

This form is useful in dealing with airplane propellers, but since marine propellers work in water of practically constant density, we need not introduce density which will be taken care of by the constants used."

It is the radical change in density of air in going from sea level to a high altitude, say, of 20,000 feet, and the limit on the revolutions of the airplane engine that make a change in pitch desirable in the case of an airplane propeller; and this is one of the reasons that controllable pitch propellers have come into such wide use for airplanes.

But we are concerned with marine applications in water of relatively constant density. As a preliminary explanation necessary to illustrate a few fundamentals, the following excerpts are quoted from a prior article (3):—

"If shaft horsepower is used, the subscript 'P' is attached to 'B'; and if 'useful' horsepower is used, the subscript 'U' is attached. Additional subscripts '3' and '4' are used to designate 3 or 4-bladed propellers. Thus B_{u3} is the basic coefficient for 'useful' horsepower and 3-bladed propellers . . ."

"Taylor's design data for B_{u3} are presented in the form of contour curves in his Figure 208(4). A skeleton outline of that figure, with additional dotted lines for explanatory purposes is reproduced herewith as Figure 1."

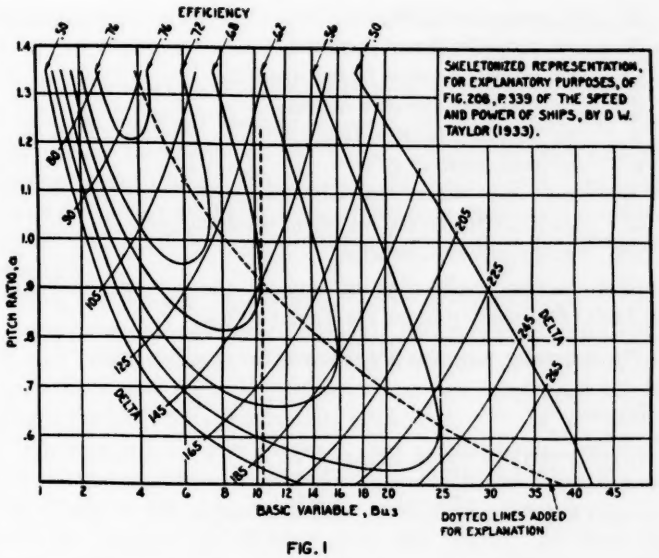

EFFICIENCY
SKELETONIZED REPRESENTATION, FOR EXPLANATORY PURPOSES, OF FIG. 208, P. 339 OF THE SPEED AND POWER OF SHIPS, BY D W. TAYLOR (1933).
PITCH RATIO, a
BASIC VARIABLE, B_{u3}
DOTTED LINES ADDED FOR EXPLANATION
DELTA

FIG. 1

"It will be seen that for any given B_{u3} (width and thickness of blades remaining constant) there is one most efficient propeller (neglecting cavitation). For example, if B_{u3} is fixed at 10.4 the most efficient propeller is where the vertical dotted line representing $B_{u3} = 10.4 =$ constant is tangent to an e_p contour. *At any other point,* e_p is less. At this point of tangency $e_p = .68$; $a = .92$; $\delta = 145$."

To define these new symbols and summarize all those which will be used in this discussion, the following list is given:—

B_{u3} = basic coefficient for useful horsepower and 3-bladed propellers.
V = speed of ship in knots.
V_A = speed of advance in knots.
w = wake fraction.
t = thrust deduction.
SHP = shaft horsepower.
EHP = effective horsepower.
U = useful horsepower.

N = propeller RPM.
T = propeller thrust in pounds.
Q = propeller torque in foot-pounds.
d = propeller diameter in feet.
p = propeller pitch in feet.
a = pitch ratio = p/d.
e_p = "open water" propeller efficiency.
δ = a dimensionless coefficient involving *size*.
P.C. = propulsion coefficient.

(For further explanation of any of these terms, and the methods of measuring them, see Taylor (1).)

The following formulas are required for this discussion:

$$B_{u3} = \frac{NU^{0.5}}{V_A^{2.5}} \qquad \text{I}$$

$$U = (EHP) \div (\text{Hull Efficiency})$$

$$= (EHP) \div \frac{(1-t)}{(1-w)} = \frac{(EHP) \times (1-w)}{(1-t)} \qquad \text{II}$$

$$V_A = V \times (1-w) \qquad \text{III}$$

$$\delta = Nd/V_A \qquad \text{IV}$$

$$e_p = \frac{101.33TV_A}{2\pi QN} \qquad \text{V}$$

$$\text{P.C.} = e_p \times \frac{1-t}{1-w} \qquad \text{VI}$$

$$SHP = (EHP) \div (\text{P.C.}) = U/e_p \qquad \text{VII}$$

To simplify discussion, we will ignore the possibilities of cavitation; and use the assumption that w and t are constant under all conditions. This is, of course, not strictly true, but has no appreciable effect on the points which will be discussed.

To illustrate some fundamentals, let us start with the propeller in the example quoted where $B_{u3} = 10.4$; $a = .92$; $\delta = 145$; and $e_p = .68$.

Case I—Constant Ship Speed—Variable Power.

This is the case where we maintain a constant speed of advance but require different powers by reason of such factors as towing,

fouling, winds, changes of draft, submerging a submarine, etc. It will be discussed under four subheads below:—

CASE I(a)—CONTROLLABLE PITCH—INCREASING POWER.

Suppose the EHP for a given speed is greatly increased, for example, by taking another ship in tow. Suppose we have enough reserve power that we can maintain that given speed. Suppose we desire to vary the pitch of the propeller to maintain a constant RPM. What will be the new pitch and what will be the effect on efficiency?

Now the diameter, d, of the propeller is constant—we do not have a controllable diameter propeller. By hypothesis in this case N and V_A are constant. *Therefore* δ *is constant. Our propeller can never depart from the parameter* $\delta = 145$. Hence we cannot give it the pitch for the maximum efficiency.

For ease in looking at Figure 1, take an exaggerated example. Let the power increase be such that B_{u3} is increased from 10.4 to 14. Delta = 145 intersects $B_{u3} = 14$ at pitch ratio (a) = 1.2; and this reduces the efficiency from the original .68 down to $e_p = .59$.

Special Note: Actually, of course, the efficiency would be worse for two reasons; (a) the larger hub required for a controllable pitch propeller is shown by Taylor (5) to reduce efficiency a few per cent; and (b) the propellers taken from Figure 1 have a uniform pitch from root to tip of blade, while in the controllable pitch propeller this is possible only at one setting of the blades—at all other settings the pitch is distorted from root to tip. This special note applies to all subsequent discussion of controllable pitch propellers.

CASE I(b)—FIXED PITCH—INCREASING POWER.

Take the same data, but keep the pitch fixed and increase the RPM to get the increased power at the same speed. *In this case "a" is constant. Our propeller can never depart from the parameter "a" = .92.* Like the prior case, we can not have the maximum efficiency. We want to find at what revolutions and at what efficiency our fixed pitch propeller will deliver the same power as the controllable pitch propeller did when set at pitch ratio 1.2. The procedure is simple. U, V_A, and d are constant.

Hence B_{u3} and δ which were paired at 14 and 145 in the prior example, vary directly with N. Therefore we multiply the values of this pair by 1.1, 1.2, 1.3, etc., to get the values of other pairs at increasing percentages of N. If the results were plotted in Figure 1 they would start from the point $B_{u3} = 14$; $\delta = 145$ and give a line sloping downward and slightly to the right. It intersects the constant pitch line "a" = .92 at approximately $B_{u3} = 16.8$; $\delta = 174$. The propeller efficiency at this point is .60; and it would be turning about 20 per cent faster than the controllable pitch propeller.

Thus, in this case of constant speed and increased power, the fixed pitch propeller also has its efficiency reduced—but not quite so much as in the case of the controllable pitch propeller.

Case I(c)—Controllable Pitch—Decreasing Power.

Let the power decrease be such that B_{u3} decreases from 10.4 to 6. As in Case I(a), δ *remains constant.* Delta = 145 intersects $B_{u3} = 6$ at pitch ratio a = .69 and this reduces the efficiency from the original .68 down to $e_p = .56$.

Case I(d)—Fixed Pitch—Decreasing Power.

Following the same procedure as in Case I(b), we find that the propeller with the fixed pitch ratio a = .92 will develop the corresponding decreased power at approximately $B_{u3} = 4.8$; $\delta = 116$. The propeller efficiency at this point is .685 and it would be turning about 20 per cent slower than the controllable pitch propeller.

Thus, in this case of constant speed and decreased power, the fixed pitch propeller does not have its efficiency reduced at all—while that of the controllable pitch propeller is badly reduced.

Case II—Variable Speed and Power.

This is the usual case where having designed a propeller for some given full speed and corresponding power, we wish to find out how it will perform at lower speeds and their corresponding powers. It will be discussed under two subheads below.

Case II(a)—Controllable Pitch—Decreasing Speeds.

If the propeller is to revolve at a constant RPM for all speeds it should be obvious, in spite of Mr. Strandell's paper, that in decreasing from full speed to zero speed the pitch ratio (or at least

the effective pitch ratio) must decrease all the way to zero. A glance at Figure 1 will show that when the pitch ratio is reduced to .5 the best efficiency obtainable is only .54 at about $B_{u3} = 25$. At all other values of B_{u3}, the efficiency is still worse. This broad observation alone should be enough to show that at low ship speeds the efficiency of the controllable pitch propeller becomes hopelessly bad.

However, we can be more precise. If we hold N constant by a controllable pitch propeller, then δ varies inversely as V_A. In other words, if $\delta = 145$ at full speed, it equals 290 at half speed and 580 at quarter speed. A glance at Figure 1 shows that whatever the value of B_{u3}, the efficiency of a propeller is bad when δ equals or is greater than 290.

It is characteristic of ships in general that as speed decreases, the ratio $U^{0.5}/V_A^{2.5}$ increases. In the case of three widely differing classes of ships, the data for which are now before me, the ratio $U^{0.5}/V_A^{2.5}$ increased until it was 1.46 to 2.52 times as great at half speed as at full speed.

Now, if by a controllable pitch propeller we maintain a constant RPM, then B_{u3} would increase in direct proportion to the above ratio. Assume, as an intermediate value, that this ratio was doubled. Then B_{u3} would be doubled. Call it 20 in round numbers. A glance at Figure 1 shows that the intersection of $B_{u3} = 20$ with $\delta = 290$ is clear off the chart in a region of such low efficiency that Taylor did not even consider it worth plotting.

Case II(b)—Fixed Pitch—Decreasing Speeds.

If N decreases in direct proportion to V_A, so that at half speed we have half of full speed N, then of necessity δ remains constant. This does happen in many cases, and is approximated in most others as a study of Speed-RPM curves for ships will show. For this reason, we get very little variation of δ over the whole speed range when using a fixed pitch, variable RPM propeller.

If, as in the previous example, the ratio $U^{0.5}/V_A^{2.5}$ doubles when we decrease to half speed, and at the same time N is halved, then of necessity B_{u3} remains constant.

With both B_{u3} and δ constant, the efficiency remains constant.

This condition is closely approximated in the case of seagoing warships. In fact the most usual deviation from this condition

results in a slight rise of the propulsive coefficient (P.C.) at low speeds.

Mr. Strandell has presented confirmation of the two conclusions from Case II(a) and (b) above which are most damning to controllable pitch propellers.

One conclusion is that when the best fixed pitch propeller is designed for full speed and power, its pitch ratio is almost indistinguishable from that of the best propeller for lower speeds and powers of the ship.

Please refer to Mr. Strandell's Figure 28 on page 440. He credits this figure to Nordstrom (6). This figure shows the RPM and SHP per propeller required to drive a torpedo boat at various speeds using propellers of different pitch ratios. It will be noted that close to the curve for pitch ratio 1.2 is a dashed line showing the pitch ratio for the best propeller at every speed from 40 knots down to 20 knots. It will also be noted that the pitch ratio of the best propeller is so close to the pitch ratio 1.2 at all speeds as to be almost indistinguishable. In short, Mr. Strandell has presented data which confirm the fixed pitch propeller as having almost the best possible efficiency over a wide speed range.

The other conclusion is that in dropping to half speed, a constant RPM controllable pitch propeller drops to a region of intolerable inefficiency.

Please refer again to Mr. Strandell's Figure 28. It is drawn on a scale which tends to obscure the facts, but they are there nevertheless. Take a pair of dividers and mark the SHP required by fixed pitch ratio 1.11 propeller to drive at 20 knots using about 240 RPM. Then mark the SHP required by a controllable pitch propeller maintaining the full speed 520 RPM to drive at 20 knots. This shows that to maintain 20 knots the constant RPM controllable pitch propeller requires about 2.5 times more SHP than a fixed pitch propeller. It is believed that might be considered an intolerable inefficiency.

But, it is argued, even if we admit that the controllable pitch propeller has a very low efficiency at low ship speeds, the better fuel consumption of a constant RPM engine would more than offset this. Then Mr. Strandell presents data which directly refute this argument.

Please refer to his Figure 29 on page 441. This presents contour curves of constant fuel consumption for various powers and revolutions of a Diesel engine. Suppose we take 500 BHP at 600 RPM; the fuel consumption is shown to be about .372 pounds/BHP-HR. Drop to half power, 250 BHP while maintaining a constant 600 RPM; the fuel consumption increases to about .430 pounds/BHP-HR., or 1.15 times as much. But suppose that instead of maintaining constant RPM, we halve the RPM at the same time that we halve the power. Then at 250 BHP and 300 RPM we find that the fuel consumption is about .370 pounds/BHP-HR. or slightly better than it was at full power.

Whatever these data may indicate, they do not show that the fuel consumption of the proposed constant RPM engine can offset the appalling inefficiency of the controllable pitch propellers at reduced power.

Please refer to Mr. Strandell's Figures 30 and 31 on pages 446 and 447. Those figures as presented to us and as explained by their description on the preceding page contain such absurdities that it is to be hoped that they were misinterpreted when Mr. Strandell translated the work of Nordstrom (6).

Take the curve of n/n_o, which is interpreted as the ratio of low speed RPM to full speed RPM. For the controllable pitch propeller, this ratio is shown as unity (1.0) for all speeds from zero to full. In other words, this confirms the previous assumption that a *constant RPM* controllable pitch propeller is advocated.

But take this same ratio n/n_o for the fixed pitch propeller. Mr. Strandell's two figures show three cases, when this ratio at zero speed drops only to about 0.66, 0.54 and 0.76. This is absurd, as a glance at the Speed-RPM curves from official trials will show. Actually, in the case of a fixed pitch propeller, the ratio n/n_o must of necessity be zero at zero speed.

Take the curves of N/N_o, which is interpreted as the ratio of low speed power to full speed power. For the controllable pitch propellers, this ratio is shown as unity (1.0) for all speeds from zero to full. We know that the efficiency of controllable pitch propellers is intolerably low at low speeds. But it can hardly be so bad that it takes as much power to drive the ship at one knot as to drive it full speed.

If it did then the case of a 40-knot destroyer running at half speed (20 knots) would be still worse. A fixed pitch propeller requires only about 10 per cent of full power to drive a 40-knot destroyer at 20 knots. Mr. Strandell's figures imply that it would require full power or 10 times as much. This is far worse than the 2.5 times as much shown earlier.

However, in any case the data Mr. Strandell presents show that at half speed it would take between 2.5 and 10 times as much power (and corresponding fuel) to drive a destroyer with a controllable pitch propeller as it would with a fixed pitch propeller.

Take the same ratio N/N_o for the fixed pitch propeller. Mr. Strandell's two figures show three cases where this ratio at zero speed drops only to about 0.66; 0.27, and 0.77. This is absurd, as a glance at the Speed-SHP curves from official trials will show. Actually, in the case of a fixed pitch propeller, the ratio N/N_o must of necessity be zero at zero speed.

Take the curves of H/D which are curves of pitch ratio (a). For the fixed pitch propeller they are correctly shown as constant for all speeds. For the controllable pitch propeller the pitch ratio at zero speed is shown as about 0.64; 0.50, and 0.77. Inefficient as such pitch ratios are known to be, it is absurd to indicate that a ship will remain at zero speed, or even one knot, while propellers with those pitch ratios are turning at full RPM.

Since, in these two figures, the three sets of curves n/n_o, N/N_o and H/D contain implications which are absurd, we can ignore conclusions based on them.

A careful analysis makes it evident that for full speed and full power, a controllable pitch propeller can be designed which is *almost* as efficient as a fixed pitch propeller; but that at all other conditions the efficiency is worse; and that at low speeds, say below half speed, the efficiency of a controllable pitch propeller is hopelessly bad.

When, then, may a controllable pitch propeller be used properly? When all of the following conditions are met:—

(*a*) The vessel operates most of the time, say 90 per cent of the time, at full power and can afford to ignore efficiency the remaining 10 per cent of the time.

(*b*) The engine is of such nature that its RPM cannot be regulated easily, or has critical RPM's which must be avoided.

(*c*) The value of the vessel or the nature of its service is such that reliability can be ignored.

One other case is indicated: That is where we do not use the *controllable* pitch feature of the propeller, but merely use its *reversible* pitch feature. In this case it operates always at *fixed* pitch, and merely substitutes its reversing mechanism in place of the reversing mechanism on the engine.

From all this it should be apparent that only in the case of small unimportant craft is the controllable pitch propeller ever justified, and then only if we are compelled to use an engine the speed of which is difficult to regulate or reverse.

The case of combatant warships is different. Reliability is of prime importance and can never be ignored. Fuel economy is almost equally important.

A careful statistical study indicates that destroyers spend more than 90 per cent of their time underway at speeds below 20 knots which corresponds to about 10 per cent of full power. Mr. Strandell's own data indicate that at 20 knots a controllable pitch propeller would require the destroyer to develop from 2.5 to 10 times as much SHP and spend a corresponding amount of fuel as would a destroyer with a fixed pitch propeller.

It would be hard to find excuses to justify that. And the imagination boggles at the thought of the *viva voce* remarks which would be made by a business man on a Congressional investigating committee.

BIBLIOGRAPHY.

(1) D. W. Taylor, *The Speed and Power of Ships.* Ransdall, Inc., Washington, D. C., 1933.

(2) Taylor, *op. cit.*, p. 97.

(3) Lybrand Smith, "Quick Approximation for Preliminary Propeller Design," JOURNAL OF A. S. N. E., Vol. XLVII, Nov., 1935, pp. 557-568. (See also "Errata" note in Vol. XLIX, May, 1937, p. 271.)

(4) Taylor, *op. cit.*, p. 339.

(5) Taylor, *op. cit.*, p. 101.

(6) H. F. Nordstrom, "Controllable Pitch Propeller" (Swedish) *Teknisk Tidskrift*, 16 July 1938, translated by J. H. Strandell, JOURNAL OF A. S. N. E. Vol. 52, No. 1, February, 1940, pp. 98-118.

Discussion, J. M. Labberton.*

I cannot agree with Mr. Strandell in his statement that, with a fixed propeller, only one operating function can be efficiently and completely satisfied. If we take an actual case and make some calculations, the situation will probably be more clear.

The curve shown is the effective horsepower versus knots of a 13,000-ton single-screw freighter and was obtained from model basin tests including both towed and self-propelled. It will be noted that the wake fraction and thrust deduction were practically equal and constant over the whole range of speeds.

Mr. Strandell says this ship resistance will not remain constant on account of head or tail winds. It might be added that resistance will also change with the weight of cargo and amount of fouling but in any event, when the propulsion machinery is designed a certain average resistance and speed is considered as a basis. This must be true even in the case of controllable pitch propellers.

Taking the ship above mentioned and assuming that it is to operate at 13½ knots with 100 R.P.M. of propeller, let us design a propeller for it by the Taylor method.

Design of propeller at 13½ knots and 100 R.P.M.

$N = \text{R.P.M.} = 100$

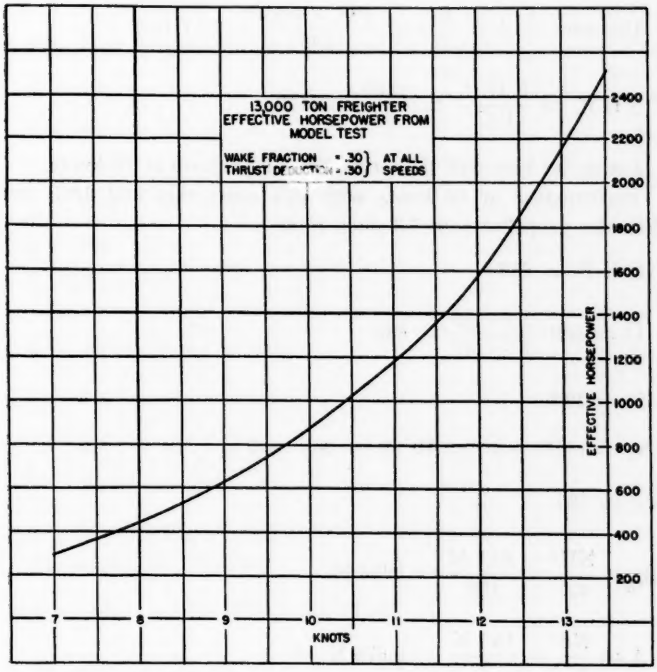
$w = .30$

$t = .30$

$v_a = v\ (1 - w) = 13.5\ (1 - .30) = 9.45$

$v_a^{\frac{5}{2}} = 275$

* Associate Professor of Mechanical Engineering, New York University.



$$U = \text{E.H.P.}\frac{1-w}{1-t} = 2500\,\frac{1-.30}{1-.30} = 2500$$

$$U^{\frac{1}{2}} = 50$$

$$B_{u_3} = \frac{NU^{\frac{1}{2}}}{v_a^{\frac{5}{2}}} = \frac{100 \times 50}{275} = 18.2$$

See Taylor's Figure 208.

For maximum efficiency

$a = .73, \quad \Delta = 198, \quad e_p = .60$

$$\text{Propulsive coefficient} = e_p\,\frac{1-t}{1-w} = .60\,\frac{1-.30}{1-.30} = .60$$

$$\text{Diameter} = d = \frac{\Delta\, v_a}{N} = \frac{198 \times 9.45}{100} = 18.7 \text{ feet}$$

$$\text{S.H.P.} = \frac{\text{E.H.P.}}{\text{P.C.}} = \frac{2500}{.60} = 4170$$

Let us see how well this propeller will perform at 10 knots.

Performance at 10 knots with this same ship and 18.7 feet diameter propeller with 7.3 pitch ratio.

$$\text{E.H.P.} = 880$$

$$U = 880\ \frac{1 - .30}{1 - .30} = 880$$

$$U^{\frac{1}{2}} = 29.7$$

$$v_a = v\ (1 - w) = 10\ (1 - .30) = 7$$

$$v_a^{\frac{5}{2}} = 130$$

$$B_{u_3} = \frac{NU^{\frac{1}{2}}}{v_a^{\frac{5}{2}}} = \frac{29.7\,N}{130} = .2285\,N$$

$$\Delta = \frac{Nd}{v_a} = \frac{18.7\,N}{7} = 2.675\,N$$

See Taylor's Figure 208.

$$B_{u_3} = 15.9, \qquad \Delta = 187, \qquad N = 70$$

$$e_p = .62$$

$$\text{Propulsive Coefficient} = .62\ \frac{1 - .30}{1 - .30} = .62$$

$$\text{S.H.P.} = \frac{880}{.62} = 1420$$

Thus we see that there is some gain in efficiency in operating at 10 knots and the propeller turns at 70 R.P.M. or in exact proportion to the speed.

Let us now design a new propeller for this 10-knot condition.

Design of propeller at 10 knots and 70 R.P.M.

$N = 70$

$w = .30$

$t = .30$

$v_a = v\ (1 - w) = 10\ (1 - .30) = 7$

$v_a^{\frac{5}{2}} = 130$

E.H.P. $= 880$

$$U = 880\ \frac{1 - .30}{1 - .30} = 880$$

$U^{\frac{1}{2}} = 29.7$

$$B_{u_3} = \frac{NU^{\frac{1}{2}}}{v_a^{\frac{5}{2}}} = \frac{70 \times 29.7}{130} = 16$$

See Taylor's Figure 208.
For maximum efficiency

$a = .78, \quad \Delta = 185, \quad e_p = .62$

$$\text{Propulsive coefficient} = e_p\ \frac{1 - t}{1 - w} = .62\ \frac{1 - .30}{1 - .30} = .62$$

$$\text{Diameter} = d = \frac{\Delta\ v_a}{N} = \frac{185 \times 7}{70} = 18.5$$

$$\text{S.H.P.} = \frac{880}{.62} = 1420$$

Thus, we have a propeller which is virtually the same as the original one, slightly smaller but no more efficient.

So the fixed propeller does operate efficiently at other than full power and speed.

It may then be contended that the operation at lower R.P.M. is a great handicap and that the controllable pitch propeller permits the full load R.P.M. at 10 knots. Let us investigate the effect of a change in pitch but retaining the 100 R.P.M.

Pitch of propeller at 10 knots and 100 R.P.M. and 18.7 diameter

$N = \text{R.P.M.} = 100$

$w = .30$

$t = .30$

$v_a = v\ (1 - w) = 10\ (1 - .30) = 7$

$v_a^{\frac{5}{2}} = 130$

E.H.P. $= 880$

$$U = 880\ \frac{1 - .30}{1 - .30} = 880$$

$U^{\frac{1}{2}} = 29.7$

$$B_{u_3} = \frac{NU^{\frac{1}{2}}}{v_a^{\frac{5}{2}}} = \frac{100 \times 29.7}{130} = 22.8$$

$$d = \frac{\Delta\, v_a}{N} = 18.7 = \frac{7\,\Delta}{100}, \quad \Delta = 267.5$$

See Taylor's Figure 208.

$a = .40, \qquad e = .30$ or less

$$\text{Propulsive coefficient} = .30\ \frac{1 - .30}{1 - .30} = .30$$

$$\text{S.H.P.} = \frac{880}{.30} = 2930 \text{ or more.}$$

Thus it is seen that the efficiency has been so lowered by decreasing the pitch that more than 100 per cent increase in power is needed.

No loss in efficiency has been charged to the controllable pitch propeller which will probably be due to the hub design.

Therefore it is apparent that the fixed pitch propeller, provided it is properly designed, is best for ordinary ships.

In the case of submarines or tugs, where the resistance varies greatly, there may be some field for a controllable pitch propeller.

I do not think the comparison between ships and airplanes as regards propellers holds good here. Airplanes must accelerate rapidly, climb and fly in air of varying density which is not true in the case of ships. An airplane's resistance is continually changing. The time spent by a ship in accelerating in percentage of the total time traveling is so small that I doubt if special consideration to this feature in design is justifiable.

NOTES.

INDEX TO NOTES.

Axial Vibrations of Engine Crankshafts.
—The British Motor Ship, London, England, August, 1940.

Uranium 235—Power Fuel of the Future?
—Power, New York, N. Y., July, 1940.

"Sea Arrow"—C-3 Type Cargo Vessel.
—The Log, San Francisco, Calif., August, 1940.

Shipbuilding on a Production Basis.
—The Welding Journal, Easton, Pa., September, 1940.

The Salvage of H. M. S. "Thetis."
—Engineering, Hayes, Middlesex, England, July 19, 1940.

Motor Fuels of the Present and Future.
—Journal, Western Society of Engineers, Evanston, Ill., April, 1940.

Miscellanea of Interest to Naval Engineers.
Smooth Speed Control of Wound Rotor Motors.
—Power, New York, N. Y., September, 1940.

Application of Fan Laws.
—Combustion, New York, N. Y., July, 1940.

Optical Plastic.
—Mechanical Engineering, Easton, Pa., August, 1940.

AXIAL VIBRATIONS OF ENGINE CRANKSHAFTS.

The following is a translation of a paper by P. Draminsky and T. Warming, engineers of Burmeister and Wain, prepared for the Bureau Veritas, Paris. This translation is reprinted from August, 1940, issue of the British Motor Ship, published in London, England.

It is well known that severe axial vibrations may arise in a crankshaft of a marine Diesel engine at moderate and high powers. These vibrations are sometimes very violent, and in particular cases they have caused a crankshaft to break.

The idea has arisen that vibrations of this nature may be due to the direct action of the combustion pressure, tending to lengthen the crank by bending the pin. However, experience has shown that axial vibrations originating in this way are of little importance.

All cases of serious axial vibration that it has been possible to examine hitherto are due to another cause, namely, the simultaneous presence of relatively severe torsional vibrations having the same frequency as the axial vibrations.

In order that this condition should arise it is necessary that the following circumstances should exist:—

1. The frequency of the axial vibrations should coincide approximately with that of the torsional vibration.
2. Severe torsional vibrations must occur at varying speeds of revolution.

It follows that instances of dangerous axial vibration are very rare in practice, since the first condition depends upon an unfortunate chance, and the second is rarely fulfilled in the case of shafts which are carefully calculated in order to avoid torsional vibration.

The methods of calculating the natural frequency of torsional vibrations are well known. On the other hand, calculations concerning axial vibrations have not yet been examined very carefully. In what follows, a formula is given for normal marine Diesel engines. This indicates the frequency of the axial vibrations of the first order, that is to say, those in which the node is found at the thrust shaft and the greatest amplitude at the forward end of the shaft. The curve of amplitude is almost sinusoidal.

Referring to Figure 1, the formula is as under:—

$$W_c = \text{natural frequency} = \frac{\pi^2}{4}\frac{EF}{ML} \quad .. \quad .. \quad (1,$$

$$\text{and } n_c = \text{critical speed} = \frac{60W_c}{2\pi}$$

In this formula

E = coefficient of elasticity or 2.1×10^6 kg./cm.^{2}

F = the transverse section of the crankpin in cm.^{2}

M = p.m. = mass of the crankshaft between the forward end and the thrust bearing (kg./sec.^{2}/cm.).

p = number of cylinders.

L = total length = $pl = p(l_1 + l_2 + l_3 - l_4)$cm.

$$l_1 = FR^2\frac{e}{\frac{\pi D^4}{64}} + \frac{2}{3}\frac{R}{\frac{bh^3}{12}}$$

l_2 = distance between centres of cylinders.

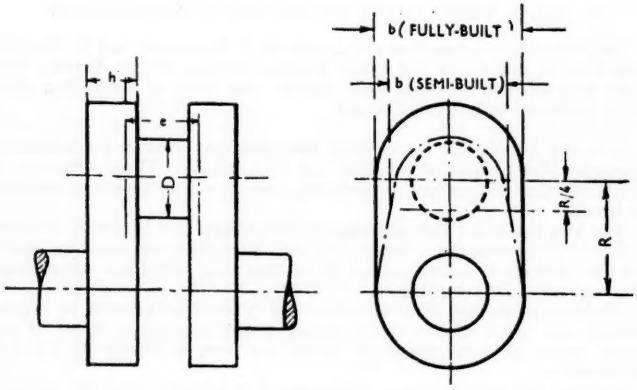


Fig. 1.

$$l_3 = 2\frac{FER}{bhG} = 5.1\frac{FR}{bh}$$

$$l_4 = kFR^2\left(\frac{e}{\frac{2\pi D^4}{64}} + \frac{R}{\frac{2bh^3}{12}}\right)$$

l_1 represents the length of a shaft which gives the elongation to which a crank will be subjected under the influence of the bending moments on the crankpin, and web, by an equal axial force, on the hypothesis that the shaft is freely supported in the bearings.

l_2 introduces the elongation due directly to the tensile strength.

l_3 takes account of the elongation arising from the shearing of the crank arm.

l_4 represents a reduction to take account of the fact that the shaft constitutes a continuous beam. The constant k as an erection factor depends on the angles of α_1, α_2 of adjoining cranks.

In general practice l_2, l_3, l_4 cancel out, so that the formula becomes

$$l_1 = 8FR^2\left(\frac{8e}{\pi D^4} + \frac{bh^3}{R}\right)$$

In marine engines with long shafts the frequency of the axial vibrations generally lies above half-way between the frequency of torsional vibrations of the first and second order. In the case of engines having very short intermediate shafts (and perhaps in other cases), in which the frequency of torsional vibrations of the first order is relatively high, it may happen that this frequency coincides with that of the axial vibrations.

To understand how torsional vibrations can give rise to axial vibrations, we may take the case of a shaft with only two cranks set at an angle α (see Figure 2).

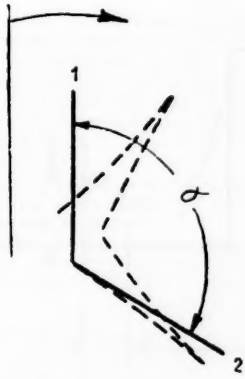


Fig. 2.

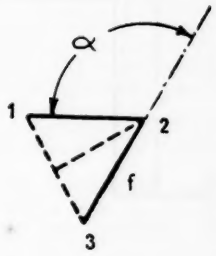


Fig. 3.

It is assumed that the shaft is fitted in the third bearing whilst being subjected to a torsional moment in the direction of the bending applied to the first bearing. If the bearings 1 and 2 can move freely the shaft will be twisted towards the dotted lines, and the crankpins 1 and 2 will be displaced, as indicated in Figure 3. The length f represents the displacement of the crankpin, caused, for each crank, by the torsion of the crankpin and the bending of the arm.

f may be taken as equal to $\frac{1}{2}$ Rx, in which x represents the rotation of one of the ends of a crank in relation to the other.

The expression is particularly convenient in the case of multi-cylinder engines, in which x is the difference between the angular amplitudes of the adjacent cranks.

The torsional effect has not resulted in any modification of the shaft in the longitudinal direction. However, the bearings cannot move freely in the transverse direction, and the axes of the bearings should be in a straight line. In consequence, the crankpin 2 must be displaced transversely towards the axis, passing from the point 1 to the point 3, that is to say, a distance of

$$f \cos \tfrac{1}{2}\left(180 - \alpha\right) = f \sin \tfrac{1}{2}\alpha.$$

For each of the cranks this displacement can be resolved into components perpendicular and parallel to the crankshaft. This latter component, which will have the following value for each crank,

$$f \sin \tfrac{1}{2}\,\alpha \sin \tfrac{1}{2}\left(180 - \alpha\right) = f \sin \tfrac{1}{2}\,\alpha \cos \tfrac{1}{2}\alpha = \tfrac{1}{2} f \sin \alpha.$$

will cause a noticeable modification in the length of the shaft.

For a group of two shafts this length variation will be the same as that of a shaft fixed at one end and subjected at the other end to the action of a force, giving a displacement transversal f sin α in the plane of the crankcase (see Figure 4).

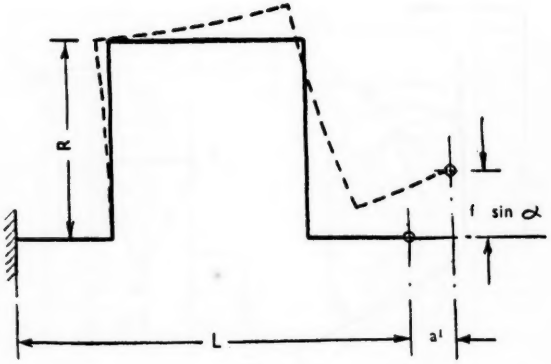


Fig. 4.

According to calculations relative to bending of the webs and pins, the variation in length will be given approximately by the formula

$$a^1 = \frac{3}{4}\frac{R}{L} f \sin \alpha \quad .. \quad .. \quad .. \quad .. \quad (2)$$

which reaches a maximum when $\alpha = 90$ degrees.

For shafts with three cranks or more, provided with bearings between each crank, it is possible to use the same calculations as with shafts having two cranks, that is to say, by first determining the transverse movement of the crankpin with a free shaft under the action of torsion. This is quite simple and resolves itself merely in an extension of Figure 3. But if it is attempted to bring all the cranks in a straight line, it becomes very complicated to determine exactly the bending moments necessary to produce the displacement towards the axis, both so far as their value and direction are concerned.

It is, however, possible to obtain a reasonable approximation by subdividing the problem and treating, individually, each group of adjacent cranks, taken successively in pairs.

In effect, if it is assumed that the crankpins 1, 2 and 3 are brought in a straight line, this operation does not result in any important modification to the relative positions of the crankpins 2, 3 and 4, so that the latter may be treated as if they were always in the same relative position.

In this way the following formula expressing the variation in total length is reached:—

$$a_t = \frac{3}{4}\frac{R}{L} \Sigma f \sin \alpha \quad .. \quad .. \quad .. \quad .. \quad (3)$$

This formula includes a factor for each group of adjacent cranks taken successively in pairs, equal to the number of cylinders less one.

For each group, f should be calculated according to the torsion in the section under consideration, and sin α should be calculated with its sign, that is to say, always reckoning α as of the same origin and in the same direction. Consequently the angle may be more or less than 180 degrees.

The formula (3) expresses the total modification in the length of the shaft under the static action of the maximum moments of torsional vibration. But it must be remembered that when the moments change their direction α_1, also changes its direction. As a result the torsional vibrations give rise to impulses on the axial vibrations of the same frequency. Moreover, α_1 depends essentially on the construction of the crankshaft. For certain crankshafts the factors in formula (3) may almost cancel out, whilst in other cases they have to be added.

Speaking generally, α_1 is not in itself very important, but if it is augmented by the effect of resonance with torsional vibrations, then the influence on the length may be considerable.

According to the general theory of vibration, excluding damping, the amplitude at the forward end of the shaft will be represented by a formula such as $a_1 = a_s F$, in which a_s represents the "static longitudinal amplitude," whilst F is the increasing factor $\frac{n_e^2}{n_e^2 - n^2}$. On the speed of resonance depends the damping action, which, according to the measurements made, appears to have an importance analogous to that of the damping of the torsional vibrations.

In certain cases the static movement a_s may be approximately equal to a_1 determined above, but to be exact it is necessary to calculate it, taking into consideration the diverse flexible reactions produced by each of the factors in equation (3). Assuming that this barely complicates the calculations it will be effected as follows:—

For the value of the elongation as calculated by formula (2) the flexible reaction will be given by the formula

$$K = ca^1 = c\frac{3}{4}\frac{R}{L}f \sin \alpha$$

in which c is the longitudinal rigidity of each crank. Now let a_1, a_2 be the actual longitudinal amplitude of the individual cranks.

As stated previously, the curve of vibrations is assumed to be sinusoidal, the node being at the thrust bearing.

Let a^1 be the differences between the amplitudes.

$$a_1^1 = a_1 - a_2 \qquad a_2^1 = a_2 - a_3$$

The sum of the work of the flexible reactions becomes $\Sigma \frac{1}{2} ka^1$ for a quarter of the cycle, reaching an average figure at the end point.

According to the general theory of vibration, the statical longitudinal amplitude c_2 is determined when the work produced by the flexible reactions is equal to the kinetic energy of the system, that is to say, by the equation

$$\Sigma \tfrac{1}{2} ka^1 = \Sigma \tfrac{1}{2} m \left(a w\right)^2$$

in which m represents the mass of the crank.

In interpolating the corresponding amplitudes,

$$\Delta_1 = 1 \; \Delta_2 = \frac{a_2}{a_1} \text{ and } \Delta^1 = \Delta_1 - \Delta_2$$

we have (a_1 being equal to a_s)

$$a_s \Sigma k \Delta^1 = a_s^2 w_c^2 \Sigma \Delta^2 \quad \text{or} \quad a_s = \frac{\Sigma k \Delta^1}{w_c^2 \Sigma m \Delta^2}$$

Replacing k by the value found above, and noting that

$$w_c^2 = \frac{\pi^2 e}{4 p^2 m} \text{ and } \Sigma m \Delta^2 = \frac{1}{2} p m$$

we have

$$a_s = \frac{6 p}{\pi^2} \frac{R}{L} \Sigma f \Delta^1 \sin \alpha$$

The practical realization of the calculation is thus only complicated by the fact that we must calculate the sum $\Sigma f \Delta^1 \sin \alpha$ in place of the sum $\Sigma f \sin \alpha$.

In practice we should calculate a_s according to the values $f = \frac{1}{2} Rx$, corresponding to the point of resonance of the torsional vibrations.

For other revolution speeds, a_s varies in proportion to the torsional amplitude. For each number of revolutions, the value of a_s thus determined must be multiplied by the factor $\frac{n_c^2}{n_c^2 - n^2}$ which reaches its maximum at the point of resonance n_c of the axial vibrations, whilst a_s reaches its maximum at the point of resonance of the torsional vibrations.

In this way the curve of the variation of a_1 may be determined with the number of revolutions. At the critical speed, namely n_c, the question of the importance of damping enters, and this constitutes the most difficult point in the calculations concerning vibration.

Nevertheless, there will be no considerable error in equalizing the relative damping effect d to that of the torsional vibrations, which gives the coefficient $F = \frac{1}{d}$ at the point of resonance.

Knowing a_1 it is easy to calculate the additional thrust exercised on the thrust bearings, and the additional fatigue stress on the cranks.

EXAMPLES.

On the test bed, axial vibrations have been noted having a total maximum amplitude (in both directions) of 8 mm. at the end of the shaft of a 12-cylinder two-stroke single-acting 8000 BHP. engine. By using a relatively heavy hydraulic brake the torsional critical vibrations have been brought down from 1020 to 660 RPM., which has been found exactly equal to that of the axial vibrations.

Figure 5 shows the crankshaft, and Figure 6 indicates the amplitude of the torsional vibrations. The curve of amplitude of the axial vibrations is purely sinusoidal, the node being at the after end where the thrust block is fitted.

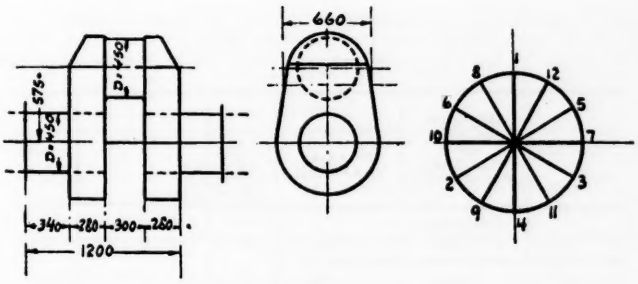


Fig. 5.

Applying the formula given above for the frequency of axial vibrations we have

$$l_1 = 2{,}750 \text{ cm.}$$
$$l_2 = 120 \text{ cm.}$$
$$l_3 = 250 \text{ cm.}$$
$$l_4 = 240 \text{ cm.}$$
$$M = 51.5 \text{ r.p.m.}$$

$$w_c^2 = \frac{\pi^2}{4} \frac{2.1 \times 10^6 \times \frac{\pi}{4} \times 45^2}{51.5 \times 12 \times 2{,}780} = 4{,}780$$

$$n_c = 660 \text{ r.p.m.}$$

which corresponds exactly to the figures obtained.

For l_4 the relatively low factor of installation of 0.19 (theoretically it should be 0.29) was used to take into consideration the fact that the engine test bed foundations give a little.

The point of resonance of the torsional vibrations of the sixth order was raised to 110 RPM.

Figure 7 shows the amplitude of the vibrations measured at the forward end of the shaft for a number of revolutions, corresponding to the point of resonance.

The maximum amplitude is 0.014 radian, corresponding to a supplementary torsional fatigue stress of 320 kilogs per square centimeter in the shaft. The coefficient of increase has the relatively low value of 13, on account of the damping effect produced by the hydraulic brake.

The calculations carried out to obtain the elongations of the shaft consequent upon torsional vibrations at points close to the speed of resonance give the result shown in Table I.

Formula 4 gives

$$a_s = \frac{6.12}{\pi^2} \frac{57.5}{120} 0.173 = 0.61 \text{ mm.}$$

For a number of revolutions adjacent to resonance, the longitudinal amplitudes have been calculated (without taking damping effect into consideration) according to the Table II.

Table I.

CYLINDERS	ANGULAR AMPLITUDE OF TORSIONAL VIBRATIONS	RELATIVE AMPLITUDE OF AXIAL VIBRATIONS	$f = \frac{1}{2} R_{\tau}$	Δ'	α	$f\Delta' \sin \alpha$
	RADIANS		mm			
1	$\varphi = 0140$	$\Delta = 1.000$	09	008	120	001
2	0137	992	17	025	120	004
3	0131	967	23	042	— 60	— 008
4	0123	925	32	058	120	016
5	0113	867	37	073	120	023
6	0099	794	46	087	— 150	— 020
7	0069	707	52	099	120	045
8	0051	608	54	108	120	050
9	0032	500	54	117	— 60	— 055
10	0013	383	54	125	120	— 058
11	— 0006	258	54	125	120	058
12	— 0025	131				173

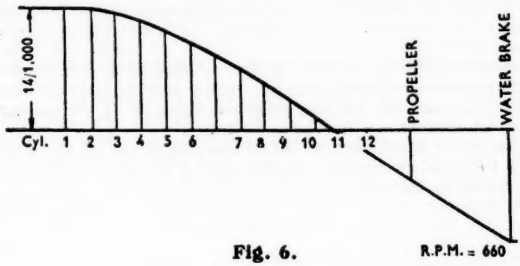


Fig. 6.

From Figure 8 it is to be seen that the longitudinal amplitudes as measured are only equal to a half those calculated. This is probably due to the fact that the foundations of the engine have not been considered as entirely rigid

Table II.

R.P.M.	RELATIVE TORSIONAL VIBRATIONS	$F = \frac{110^2}{110^2 - n^2}$	$a_1 = 0{,}61 \cdot \varphi_r \cdot F$
			mm
90	$\varphi_r =$ 23	3.0	0.4
100	43	5.8	1.5
105	67	11	4.5
110	1.00	∞	∞
115	61	11	4.1
120	39	5.2	1.2
130	18	2.5	0.3

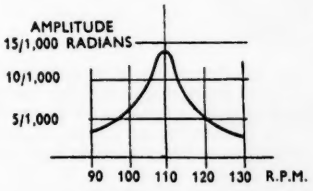


Fig. 7.
Torsional vibrations.

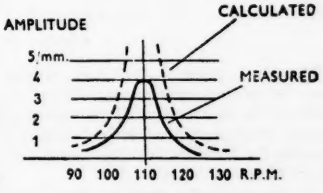


Fig. 8.
Longitudinal vibrations.

(the same hpothesis has been taken for the calculation of the frequency of axial vibrations as stated before). Moreover, the play in the bearings exercises an effect in the same direction, because if no account be taken of the resistance of the oil, the crankpins can move freely in the transverse direction to an extent equal to the radial play. This play is not without importance, as can be seen from the magnitude of f in column 4 of Table I.

The present method of calculation, which does not take count of these corrections, gives, in practice, a higher limit to the axial amplitudes. This is sufficient for all ordinary working calculations.

The maximum amplitude of 4 millimeters is equivalent to an additional thrust of 60 tons, exerted on the thrust block, and a supplementary bending fatigue stress of 400 kilograms per square centimeter.

It may be added that in using a smaller hydraulic brake giving a higher torsional critical speed frequency, corresponding to the actual installation on board ship, it has been possible to note that the maximum of the axial amplitudes falls to 0.5 millimeter and below, although their frequency has not been subjected to any change. This proves clearly that the dangerous axial vibrations are due to torsional vibrations and not to the direct action of the combustion pressure.

URANIUM 235—POWER FUEL OF THE FUTURE?

The scientific possibility of atomic power generation has now been definitely established. Although atomic power may not be a subject of immediate practical concern there is much food for thought by power engineers in the following article by Philip W. Swan, Editor of Power. This article is reprinted from the July, 1940, issue of Power, published by McGraw-Hill Publishing Company, Inc., 330 West 42nd St., New York, N. Y.

Uranium, heaviest of all metals, has three forms (chemists call them "isotopes") more alike than human triplets. In most chemical and physical respects they are practically identical. These isotopes are called Uranium 234, Uranium 235 and Uranium 238, the numbers being the respective atomic weights.

In one respect only, as far as we know now, does 235 stand out from its brothers as the Empire State Building towers above a one-story "taxpayer." It has been proved by actual laboratory tests made this year on a little sliver of Uranium 235 (in the whole world a mere fraction of a pinhead of this material has so far been isolated for experimental purposes) that a relatively slow atomic projectile impinging on the nucleus of an atom of 235 will explode it, breaking the "massive" atom up into two atoms of substances about half as heavy.

ATOMIC EXPLOSIONS.

More important, it has been proved that the fragments of this explosion have far greater energy than that of the original projectile, so that the energy released is practically all net gain. These moving fragments of a terrific atomic explosion are easily brought to rest by barriers of matter, thereby heating the barriers and delivering their energy as ordinary sensible heat, just as burning coal does.

At this point, the physicist would explain that the atomic energy so released is actually a conversion of mass into energy. About 0.1 per cent of the mass of the Uranium atom is lost in being transformed.

If every atom in one pound of 235 were thus exploded, the heat delivered for outside use would be 37,000,000,000 Btu. per pound. Uranium 235, as a fuel, is equivalent to 1370 tons of 13,500-Btu. coal. Directly or indirectly, this heat could make steam. This stetam, with present-day turbine-room equipment, could easily be converted into 2,700,000 Kwhr. of electrical energy, assuming the very conservative conversion efficiency of 25 per cent. This would be enough to operate a 100-HP. motor continuously at full load for three years.

Naturally, then, this discovery will interest the wide-awake power engineer. If he is wise, however, he will not rush off to buy any stock in Uranium power plants until he has sized up some of the difficulties that tmust be overcome before this splendid bird in the bush can become a chicken in the pot.

HARD TO SEPARATE 235.

First is the still unsolved and extremely difficult problem of commercially separating Uranium 235 from the parasitic 234 and 238 with which it is always mixed in a state of nature. Every pound of Uranium 235 recovered from natural ores is intimately mixed with about 140 pounds of 238 and about

1/120 pound of 234. Commercial Uranium metal always runs about 0.006 per cent of 234, 0.7 per cent of 235 and over 99 per cent of 238. Getting rid of the 238 is the practical problem.

Assuming that several pounds of 235 could be obtained at reasonable cost (it would be cheap at several thousand dollars per pound), there would still be numerous engineering problems to be solved in transferring the released heat to steam or some other working medium. These problems, nevertheless, seem less difficult than that of obtaining the 235.

LET'S LOOK AT SOME ATOMS.

With this preamble, it seems worth while to review, in ABC fashion, just enough atomic physics to give the reader a mental picture of how 235 works. Most power engineers have not been following this line. The explanations will cut a lot of corners, and may not be completely satisfactory to physicists, but will suffice for present purposes.

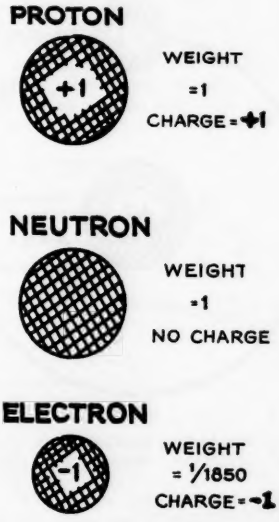


FIGURE 1.—THE BUILDING BLOCKS OF MATTER.

Figure 1 diagrams the more important basic building blocks of matter—of *all* matter from molasses candy to arsenic, from gold to cast iron. These "blocks" are proton, neutron and electron. Proton and neutron are alike in mass ("weight"), but differ electrically. Proton and electron differ enormously in mass, but have equal and opposite electrical charges. Let's call the mass of the proton 1 and its electrical charge + 1. Then the mass of the neutron is 1 and its charge zero. The mass of the electron is insignificant (1/1850), but its charge is —1.

To keep the record straight, we should note the occasional appearance of positively charged electrons, called "positrons," and the possibility that there is a tiny neutral particle, the "neutrino." Forget these; they do not concern the present discussion.

THE HYDROGEN ATOM.

Figure 2 shows the simplest and lightest of all atoms, that of hydrogen. Here we have a "solar system" consisting of one "sun," a single proton with a plus charge, around which revolves at inconceivable velocity one "planet," a single electron with a negative charge. Plus and minus attract, so the electron tries to fall into the proton, just as the earth tries to fall into the sun because of the gravitational pull. But both moving earth and moving electron tend also to move in a straight line (tangentially). The tangential tendency and the centripetal pull balance in the compromise of circular or elliptical motion.

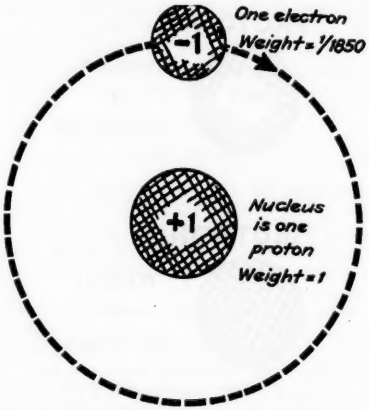


FIGURE 2.—HYDROGEN ATOM IS THE SIMPLEST AND LIGHTEST. ONE ELECTRON (WEIGHT 1/1850) REVOLVES AROUND A NUCLEUS OF ONE PROTON (WEIGHT 1).

Since the weight of the electron is negligible, the weight of this hydrogen atom is simply the weight of its proton, "1," the figure given in all chemistry books for the approximate atomic weight of hydrogen. (The number of hydrogen atoms in a pound can be expressed as "1," followed by 27 ciphers thus, 1,000,000,000,000,000,000,000,000,000.)

Please note that Figure 2 is not "to scale"—not by a long shot. Diameter of the hydrogen atom is about 1/100,000,000 of an inch. Even at that, the atom's diameter is about 100,000 times that of the electron and also 100,000 times that of the nucleus.

In the case of this ultra-simple hydrogen atom, the center, or "nucleus," consists of but one particle, a proton. All other elements are heavier than hydrogen, and have more than one proton in the nucleus. To balance these

positively charged protons, they must have an equal number of negatively charged electrons in the outer orbits. Thus, in the atom of *any* element, there will be as many electrons whirling around in various outer orbits as there are protons bunched in the nucleus. Nobody knows exactly what goes on in the nucleus, but the protons (when more than one is present) must be moving with extreme velocity.

In addition to these protons, the nucleus of the typical atom (not hydrogen) contains some neutrons. These add to the mass, though electrically neutral. To a fair degree of accuracy, the atomic weight of any substance is simply the numerical sum of the protons and neutrons in the nucleus of its atom.

It may be asked how the protons can possibly bunch together in the nucleus (since their positive charges must repel), or even how the neutrons can remain in the nucleus (since they, too, are moving and should thus tend to fly out). The physicist's answer to this is a mysterious attractive force of one mass for another which becomes very powerful at these minute distances, but fades into significance if the distance approaches the diameter of one atom.

THE URANIUM ATOM.

Figure 3, picturing the atom of Uranium 235, is even more schematic than Figure 2. It must not be taken too literally except as to counts, charges and weights. The electrons, for example, are probably moving in orbits tilted at all angles to the paper and a great variety of radii. They don't swirl around in unison like a line of horses in a circus ring. No attempt has been made to picture the true arrangement, but the numbers indicated are correct and exact.

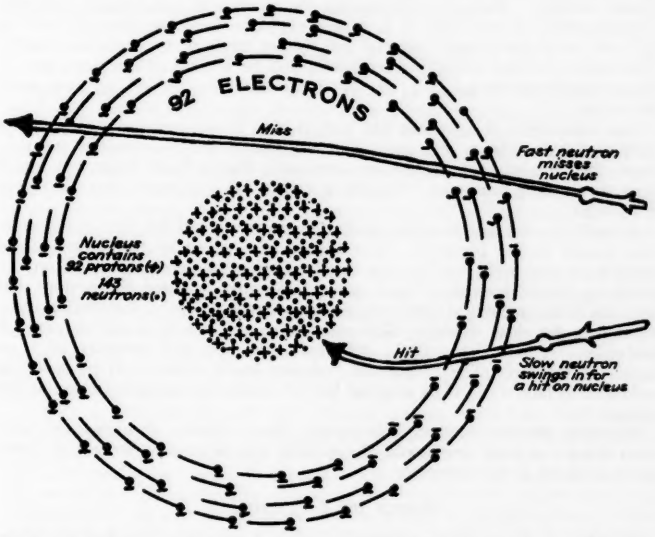

92 ELECTRONS
Miss
Fast neutron misses nucleus
Nucleus contains 92 protons (+) 143 neutrons (•)
Hit
Slow neutron swings in for a hit on nucleus

FIGURE 3.—ATOM OF URANIUM 235 CONTAINS 92 PROTONS (+) IN NUCLEUS, ELECTRICALLY BALANCING 92 ELECTRONS (—) IN OUTER ORBITS. SINCE ELECTRON WEIGHT IS NEGLIGIBLE, ATOMIC WEIGHT = 92 + 143 = 235. SKETCH IS PURELY SCHEMATIC.

The 92 moving electrons in the various outer orbits of this atom contain a lot of energy, but it is small compared with the total in the swarming 92 protons and 143 neutrons of the nucleus. Each of the 235 particles in the nucleus weighs 1850 times as much as one electron.

The energy of matter may be considered from the angle of the energy *in* the matter or of the energy one can *get out*. From the first point of view all forms of matter are approximately equal, having an internal atomic energy of about 40 trillion Btu. per pound.

To release some of this energy, the atom has to be broken up, or break up of its own accord. Radium is the classic example of the latter. It disintegrates slowly, giving off energy steadily. In 1600 years its radiation shrinks to half value.

BOMBARDING ATOMS.

Other atoms have been broken up by bombardment with fine particles—usually high-speed protons or neutrons, traveling 10,000 miles per second, or faster. The resulting explosion may give off energy (sometimes more, sometimes less, than that of the original projectile), but the number of direct hits on the tiny nucleus is so small, and the cost of generating the projectile is so large, that it's "no sale" as far as power generation is concerned. But Uranium 235 is different.

Suppose you use a "very slow" neutron projectile, one moving no faster than a molecule of air in a room at 70 F. (about 1000 feet per second). If this projectile happens to hit the nucleus of an atom of Uranium 235 it will split the atom up into two atoms of new substances of about half the original atomic weight. These two fragments fly apart with catastrophic violence. "Spart parts," in the form of 2, 3 or 4 neutrons (average about 3) will be left over from the atomic split and will fly out freely with enormous velocity. The energy in these exploding fragments will be several billion times that of the projectile used—as if a ton of dynamite were set off by one small detonator.

One interesting thing about 235 is that it is broken up much easier by a slow projectile than a fast one. There appear to be two reasons for this. First, the Uranium 235 nucleus is so unstable that a "soft blow will smash it as surely as a hard one. Second, a "slow ball" is much more likely to make a hit.

Actually the nucleus is much smaller in proportion to the size of the atom than shown in the Figure 3. The chance of a given neutron being aimed straight at this bull's eye is very small. One must generally count on the projectile being "sucked in" as it passes. As already noted, the protons and neutrons in the nucleus are drawn together by some powerful dominating force when they get close enough. This same force will act on a passing neutron projectile. A fast shot will be deflected little, and will probably miss, as shown at the top. The "slow ball," shown lower down, will probably be sucked in to land a hit, if its original line of motion is reasonably close to the nucleus.

Whatever the explanation, it is certain that a stream of high-speed neutrons breaks up very few atoms of Uranium 235, whereas a stream of slow-speed neutrons is very effective.

SEARCH FOR A "CHAIN."

The idea of atomic power calls for a "chain" reaction. We find this often in nature. You light one leaf with a match and the whole pile becomes a bonfire. The same thing happens with a gas flame or with coal on a grate.

You disturb one boulder on a steep mountain and thereby start an avalanche. All these are chain reactions. Junior sets up a row of dominos on end, trips the first and all fall down. Another chain reaction.

Applying this process to a mass of Uranium 235, you would explode the first atom with a neutron projectile fired from the outside. You might expect neutron fragments from the first explosion to explode several additional atoms and so on. Thus the disintegration of atoms would continue of its own accord until the entire mass was converted into lighter elements and the whole available 37 billion Btu. per pound released.

While physicists have been seeking something of this sort, some of us have wondered. Suppose the chain should work instantly! One pound of Uranium 235 would blow up the laboratory, the institution and probably the whole town. On the optimistic side was the thought that if this could happen nature would have accidentally touched off the combination long ago.

Chains so far obtained with Uranium 235 have not been self-perpetuating for two reasons. One is that the experimental work was conducted with a thin film of 235. Practically all the neutrons released by the primary explosions flew off without hitting any more Uranium. Most of the shots were wasted, went wild.

Now a bungling rifleman, who might miss a lone tree, couldn't miss hitting some tree or other if he fired at random in a deep forest. Same with atoms. Imagine a mass of several pounds of Uranium 235, with a cavity in the center, wherein a single neutron is released. If it misses a few nuclei it will continue on until it finally hits one and explodes it. From one to four high-speed neutrons fly off from the explosion. Each of these eventually finds a nuclear target, so the explosions build up in a geometrical series.

URANIUM 235 IS SELF GOVERNING.

Here would seem to be the basis for the catastrophic explosion already mentioned, but physicists have already learned that it cannot take place with Uranium 235, because nature has installed her own "fire extinguisher" in this element. The neutrons thrown off by atomic explosions are moving too fast to disrupt other atoms. They have to be slowed down artificially. Hydrogen atoms, in layers of water, are the best brakes. After the neutron has been slowed down enough it will find another Uranium nucleus and explode it. In this way you get a retarded chain reaction, such as you get with coal burning in air.

So you perforate your Uranium mass with voids or pipes full of water. When the reaction is started the water wastes the excess energy of the projectiles and the reaction goes on as a slow chain. Why not an instantaneous chain? Because if the reaction went faster than the water fed could carry away the heat as steam, the steam would be superheated to such a high temperature that it could not sufficiently slow down the neutrons and they would cease to smash other atoms.

Briefly, present experiments make it seem certain that a true chain reaction could be started in a mass of perhaps 5 to 50 pounds of Uranium 235, using very simple apparatus (perhaps none at all; competent physicists tell me that the neutrons in the cosmic rays always present should be sufficient to start the process). Thereafter the evolution of energy would proceed at a rate determined by the rate at which water was pumped through the mass. When water flow was stopped the evolution of energy would cease or reduce to a small value.

All water pumped through would be instantly converted to high-temperature steam.

SCIENTISTS ON THE FIRING LINE.

The history of the laboratory work behind this sensational discovery is intensely interesting, but there is space here only for the briefest summary: in January, 1939, Drs. O. Hahn and E. Strassman of Germany bombarded Uranium with neutrons, and thereafter found traces of lighter elements, having about half the atomic weight of Uranium.

Hearing of this, three American groups, within a period of a few weeks, proved by tests that the bombardment does actually split Uranium into lighter substances, with tremendous energy release. First in this race, by a few days were Prof. John R. Dunning, Prof. Enrico Fermi and collaborators at Columbia University. A few days later came confirmation from L. R. Hifstad, R. B. Roberts, M. A. Tuve and associates at Carnegie Institution of Washington.

Many laboratories in Europe and America immediately went to work on this problem, but none succeeded in getting a true chain reaction with commercial Uranium. It was suspected that Uranium 238, constituting over 99 per cent of the Uranium used, was acting as "damper." The obvious next step was to test the three isotopes separately.

First they had to be separated. This was accomplished in the Spring of this year, first by Professor Nier of the University of Minnesota, and two weeks later by scientists in the General Electric research laboratory. Nier used a "mass spectrometer" in which a stream of ionized Uranium bromide was passed through a magnetic field. This field deflected the streaming Uranium atoms in inverse proportion to their weights and thus formed three little patches of 238, 235 and 234, respectively, on the platinum target. Thereafter the Columbia scientists (Prof. Dunning, Prof. Fermi, Dr. E. T. Booth and Dr. A. V. Grosse) were able to bombard each isotope separately. They found that 238 was not at all receptive, nor was 234, whereas 235 gave the spectacular results already described.

In all the laboratories, the first step in the bombardment technique is to produce very high-speed projectiles, such as protons. The protons are accelerated either by a straight high-voltage electrical field, or by an electro-magnetic device known as the cyclotron. The cyclotron whirls the protons around in a gradually enlarging spiral at constantly increasing speed. The resulting high-speed protons are allowed to hit a beryllium target. This, in turn, gives off a shower of high-speed neutron projectiles to attack the sample of Uranium.

SUPPLY OF URANIUM.

The best Uranium ore is "pitchblende," which has been used for years as the commercial source of radium. At present there are pitchblende mines in Western Canada, in Australia, in the Belgian Congo and in Germany. There are no rich deposits in the United States, but some low-grade Uranium ore is found in Colorado in the form of Carnotite. Uranium oxide is 65 to 90 per cent of the total weight of pitchblende.

Present price of Uranium oxide (U_3O_8) is about $5.00 per pound, whereas the commercial Uranium metal sells for about $40.00. It is easy to imagine that this could be reduced to $10.00 or less if a commercial demand arose. However, this pound of commercial Uranium metal would contain only 1/140 pound of the desired 235 isotope, so that the cost of the latter, even if there were no extraction costs, might be over $1000 per pound.

It probably won't make any particular difference whether this isotope is separated in metallic form, or as an oxide. In any case the problem of

separating isotopes so nearly similar in all physical and chemical properties is one of enormous difficulty. This, more than any one thing, may delay for decades the application of Uranium 235 as a commercial fuel.

FUTURE APPLICATIONS.

Waving aside all these practical difficulties, and looking forward to an imaginary future state in which they have been solved, it is interesting to attempt prediction of the effect on commercial generation of steam and power. To idealize the case, let us assume that Uranium cost per unit of energy output is negligible, and that plant investment and labor costs are the same as now.

In that case, for a power or steam station, the total possible saving would be the present cost of coal. In a central station this saving would run from 2 to 4 mils per Kwhr. It would even be less (assuming no change in coal prices) if we should base our comparison on the higher thermal efficiency of the steam station of the future. In any case, this saving in the cost of raw heat would be important, but not revolutionary. It would be less important than the savings produced by the change from the carbon filament lamp to the tungsten lamp, or from the tungsten lamp to the fluorescent. The effect on process steam costs in industry would be more important, since the total amount of coal burned to make process steam is two or three times that used by the central stations.

Because of its extreme concentration of energy, Uranium 235 has an immense appeal to the imagination as the future fuel for house heating and for the powering of planes, autos, ships, etc.

In the household ten tons of coal could be replaced by the consumption of 1/140 pound of Uranium. With no improvement in conversion efficiency a car that runs 15 miles on one gallon of gasoline would run about four million miles on one pound of Uranium.

There is at least one joker in this delightful picture. In the case of the home you might have to stock up with fuel for the next thousand years, because (it now seems) the 235 would not "burn" unless you had a mass of at least five pounds. Same may hold for automobiles. Who would want to "fill the tank" for twenty million miles?

Fundamentally it would be a matter of fixed charges on the minimum workable Uranium inventory, and the "turnover," of that inventory. On the other hand, the inventory problem should not be too serious for the central station or industrial power plant of medium and large size.

Obstacles such as these make early practical application of atomic power on a substantial scale unlikely. Nevertheless, Uranium 235 gives us the "makings" of atomic power plants. In the light of the history of science and engineering, eventual application seems probable—perhaps within our lifetime.

SEA ARROW—FIRST C-3 TYPE CARGO VESSEL TO BE COMPLETED ON THE PACIFIC COAST.

This description and cuts of the *Sea Arrow* are reprinted from August, 1940, issue of The Log, published by The Log Publications, Inc., 605 Market Street, San Francisco, Calif. The *Sea Arrow* was acquired by the Navy on July 8, 1940, for conversion to a seaplane tender and has been renamed U. S. S. *Tangier*. The conversion is being accomplished by the Moore Ship Building Corp., of Oakland, Calif.

Hailed as the first ocean-going vessel built on the Pacific Coast in two decades, the Maritime Commission's C-3 design cargo steamer *Sea Arrow* has been completed by the Moore Dry Dock Company, Oakland, Calif., and delivered to the Maritime Commission. Built at a cost of $2,838,738 the *Sea Arrow* is the first of four sister vessels awarded the Moore firm, at least two of which are expected to be operated by Moore & McCormack in their recently acquired Pacific Republics Line between United States Pacific ports and the East Coast of South America.

For many years the United States was far behind other maritime nations in respect to modern, speedy cargo carriers. With passage of the Merchant Marine Act of 1936 for the purpose of rehabilitating the American Merchant Marine, and the formation of the Maritime Commission to put the intent of the Act into force, a long-range schedule of 50 ships per year for a period of ten years was soon established as a reality.

Exclusive of several specially designed vessels for private owners, the *Sea Arrow* is one of over thirty vessels completed and delivered to date in the Maritime Commission's program. Performances of previously completed vessels indicate that they are the most efficient cargo carriers in the world. Vessels that will be capable of meeting the competition of other nations' merchant ships.

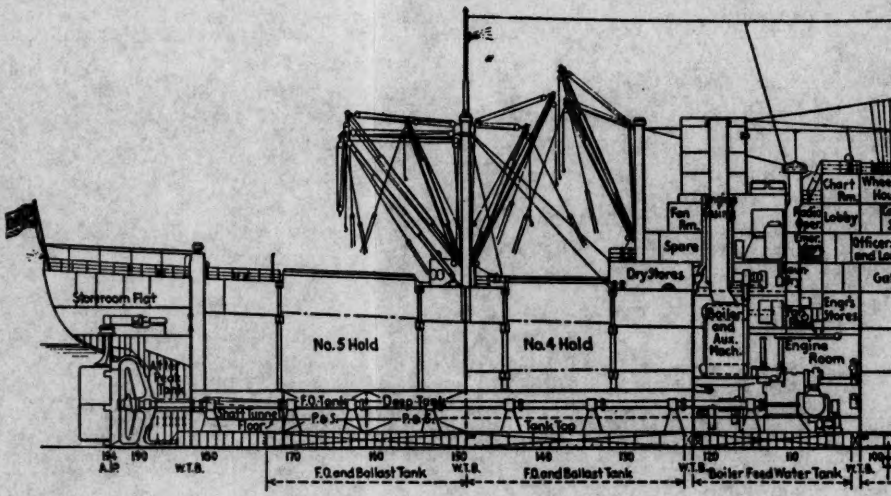
SEA ARROW.

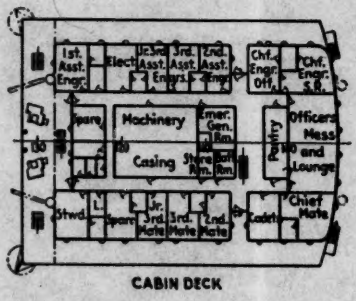
PRINCIPAL DATA AND CHARACTERISTICS.

Length, over all, feet and inches	492–00
Length, between perpendiculars, feet and inches	465–00
Beam, molded, feet and inches	69–06
Depth, molded to shelter deck, feet and inches	42–06
Depth, molded to freeboard deck, feet and inches	33–06
Draft, loaded, feet and inches	28–06
Gross tons	7,773
Net tons	4,585
Displacement at full load draft, tons	17,615
Deadweight tons, approximate total	12,000
Deadweight, cargo, tons	9,860
Weight of vessel, light tons	5,680
Bale capacity, cubic feet	730,541
Propulsion: single-screw, geared turbines.	
Shaft horsepower, normal	8,500
Shaft horsepower, maximum	10,625
Boilers: (2) Watertube, 465 pounds, W.P.	
Speed, service, knots	16.5
Speed, maximum on trials, knots	19.3
Cruising radius, miles at normal speed	12,000
Officers and crew	43
Passengers	12
Classification: American Bureau of Shipping.	

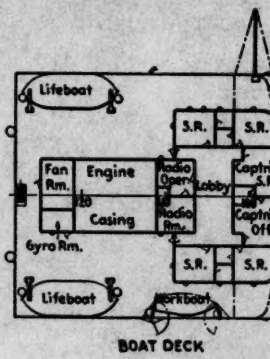
The *Sea Arrow* is a single-screw shelter deck type, steel cargo vessel of 492 feet overall length, and having a raked stem and cruiser stern. She is built to the highest class of the American Bureau of Shipping, and meets all requirements of the Bureau of Marine Inspection and Navigation, U. S. Public Health Service and other agencies.

The shell plating of the hull is riveted, but all interior structures are arc-welded by the "Unimelt" automatic machine process. The welded con-

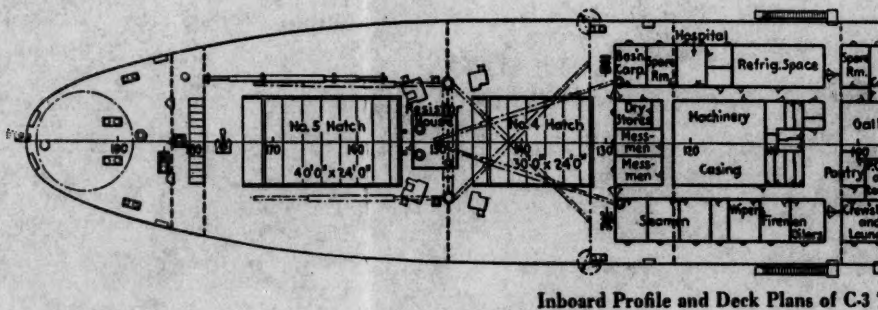




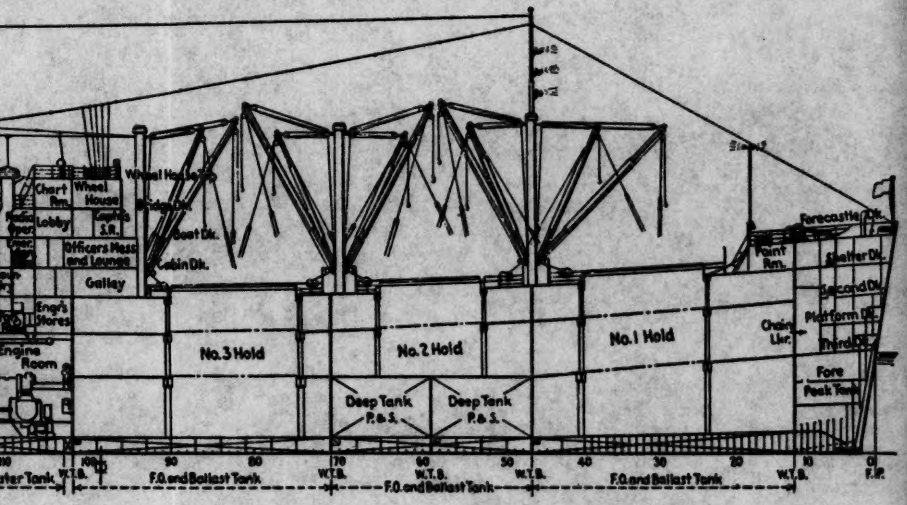
CABIN DECK

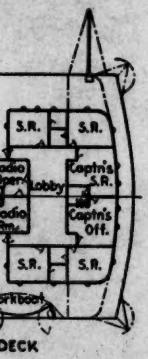


BOAT DECK

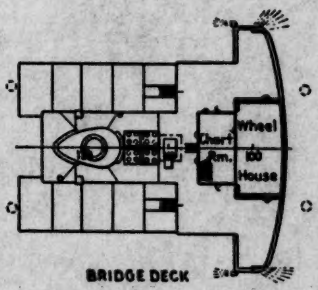


Inboard Profile and Deck Plans of C-3

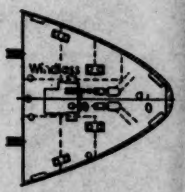




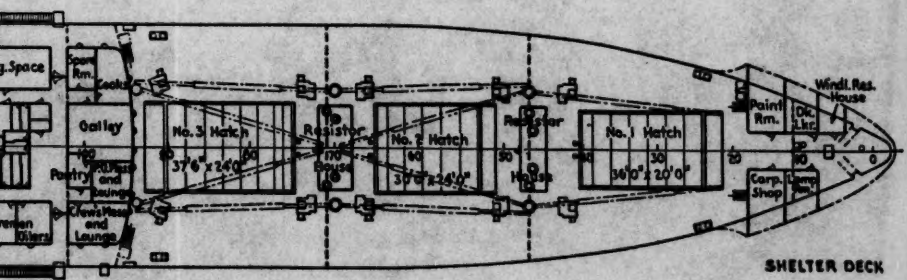
DECK



BRIDGE DECK



FORECASTLE DECK



SHELTER DECK

Plans of C-3 Type Cargo Steamer *Sea Arrow*

struction features made possible the pre-fabrication of large sections, weighing as much as 40 tons, outside of the vessel itself and in positions more favorable to use of the welding equipment. The completed sections were then hoisted into place by a heavy capacity Whirley crane and assembled into the vessel's structure.

The hull is subdivided by 7 bulkheads which gives 8 compartments. There are 5 cargo holds, machinery space and fore and after peaks. Three holds are forward of the machinery space and two aft. Hold capacities are: No. 1, 105,593 cubic feet; No. 2, 134,141 cubic feet; No. 3, 180,642 cubic feet; No. 4, 142,860 cubic feet; and No. 5, 110,853 cubic feet. There is also 12,276 cubic feet of dry cargo space in the 'tween deck over the machinery compartment. Total deadweight capacity is 11,920 tons including 9860 tons cargo capacity.

In the No. 2 lower hold, deep tanks are provided port and starboard for carrying 1560 tons of liquid cargo. Additional liquid cargo tanks of 270 tons capacity are provided each side of the shaft tunnel in No. 5 lower hold. Fuel oil is carried in five double bottom tanks, and in deep tanks at the after end of No. 5 lower hold. Total fuel capacity is 1629 tons or approximately 10,800 barrels. The double bottom tanks are also connected for water ballast. A fuel oil settling tank is provided in the after starboard corner of the engine room. Boiler feedwater capacity of 314 tons is provided in the No. 4 double bottom tank under the machinery space. Domestic fresh water capacity of 84 tons is provided in separate tanks on the second deck.

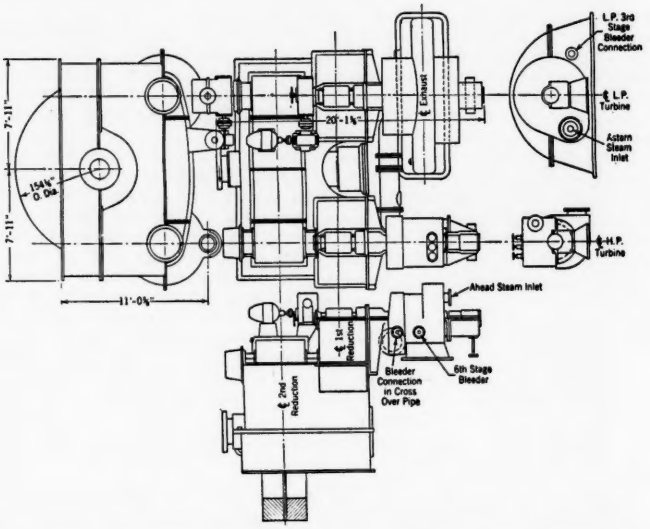
The second and third decks below the shelter deck are continued for the entire length of the vessel except in way of machinery space. The third deck forms the top of the deep tank in No. 2 hold and the top of the deep tank and shaft tunnel in No. 5 hold. Bulkheads are watertight to the second deck with the exception of the fore and after collision bulkheads which are watertight to the shelter deck. The vessel is a one-compartment ship with respect to stability in flooded condition.

Above the shelter deck amidships is the superstructure consisting of cabin deck, boat deck and bridge deck. On the shelter deck is located the galley, crew and petty officers' messes, dry stores, ship's stores, refrigerator space, hospital and crew quarters. On the cabin deck is located the officers' quarters, officers' mess and lounge, spare room, emergency generator and battery rooms. On the boat deck is the captain's quarters, three passenger staterooms, radio rooms, gyro room, and fan room. Forward on the shelter deck is the paint and lamp rooms, carpenter shop, and deck locker. On the bridge deck is the pilot house and chart room. All accommodations and passageways are fireproofed throughout, panelled with Johns-Manville "Marinite" steel faced on both sides. All quarters are mechanically ventilated and heated with conditioned air. The galley is completely equipped with modern electrical cooking equipment furnished by the Edison General Electric Appliance Company.

Officers' and crew quarters, messrooms, interior passages, and pilot house deck totaling 7500 square feet area are covered with Case Magnesite deck covering furnished and applied by the L. S. Case Company. This decking provides a fireproof, water resistant, lightweight, long-wearing protective covering for the steel decks. It is a plastic covering applied over expanded metal spot-welded to the deck.

Lifesaving equipment consists of two 28-foot metallic lifeboats with sufficient capacity to take care of the entire ship's complement and passengers. There is also provided one 18-foot metallic workboat. All boats and davits were furnished by the Welin Davit & Boat Corporation.

For fire protection, there is installed in all cargo compartments a Richaudio smoke detecting system with a detector cabinet in the pilot house. For protection in the machinery space there is provided a Lux carbon dioxide fire extinguishing system. All fire detection and extinguishing apparatus was furnished by Walter Kidde & Company.



SCHEMATIC DIAGRAM SHOWING LAYOUT OF DE LAVAL TURBINE PROPULSION MACHINERY.

Navigating equipment is of the most modern type. There is installed a gyro-compass with two repeaters and a gyro-pilot, and course recorder were all furnished by the Sperry Gyroscope Company. Rudder angle indicators and the mechanical telegraph system were furnished by the Bendix Aviation Corporation. Radiomarine Corporation furnished the radio equipment. Henschel Corporation furnished the general alarm and annunciator systems, also the revolution counter. For keeping check on the depth of water at any time a fathometer was installed by the Submarine Signal Corporation. The Lietz Company furnished the sounding machine.

Cargo is handled by sixteen 5-ton, and one 30-ton booms mounted on five pairs of kingposts served by 16 single-geared and 2 double-geared American Engineering Company's winches powered by a 50-horsepower General Electric motors. Other deck machinery furnished by American Engineering Company consists of electro-hydraulic steering gear, electric-driven spur-gear windlass powered by 70-HP. General Electric motor, and one reversible capstan powered by a 50-HP. General Electric motor.

The electro-hydraulic steering gear is of the most modern type. There are two opposed cylinders with ram on each side of the center line constituting duplicate units, the unit on either side may be operated independently. Oil

pressure is supplied to the cylinders in operation by either of two independent, variable delivery Hele-Shaw hydraulic pumps each driven by a constant-speed, single direction 50-HP. General Electric motor. Power is transmitted to the rudder stock through links from the ram crossheads. To increase propulsive efficiency the vessel is fitted with a Contraguide rudder.

MACHINERY.

The main propulsion machinery consists of De Laval cross-compound turbines designed to develop 8500 normal shaft horsepower, and connected to the propeller shafting by De Laval double helical reduction gears turning the propeller at 85 RPM. at the normal service speed of 16.5 knots. Similar machinery is also supplied to the *Sea Arrow's* three sister vessels building at Moore's and six similar vessels built by the Federal Shipbuilding & Dry Dock Company.

The high pressure turbine is of the impulse type, has 11 stages and at normal speed will turn 5012 RPM. The low pressure turbine has 7 ahead and 3 astern stages normally turning 3459 RPM. Steam is supplied to the throttle at 440 pounds gage and at 740 degrees F. temperature, and the low pressure turbine exhausts to a Worthington condenser at 28.5 inches vacuum referred to a 30-inch barometer. Maximum designed power is 9350 SHP. at 88 RPM. of the propeller. The astern element incorporated in the low pressure casing is designed to develop not less than 40 per cent of the ahead power.

The low speed gear with a pitch diameter of 153.75 inches is of welded steel construction with a forged steel rim. The reduction gears are housed in casings of cast iron and welded steel construction, split for ready access to bearings and rotating parts. The main thrust bearing is a Kingsbury six-shoe segmental type, and is designed to absorb a maximum thrust of 170,000 pounds.

The main condenser, supplied by Worthington Pump & Machinery Corporation, is of the 2-pass type with 7800 square feet of cooling surface. Under normal operating conditions it will handle 53,700 pounds per hour with 28.5 inches vacuum and 75 degrees F. injection water. The Worthington air ejector is of the twin 2-stage type with inter and after condensers. The two Worthington condensate pumps are of the vertical 2-stage centrifugal type. The main circulating pump is of the vertical centrifugal type with a capacity of 12,000 gallons per minute, driven by 100-HP. Westinghouse motor.

Steam is generated by two Foster-Wheeler " D " type boilers, at 465 pounds per square inch and 765 degrees F. total temperature at the superheater outlet. Normal evaporation is 42,870 pounds of steam per hour, and maximum evaporation 64,820 pounds at the designed pressure of 525 pounds. The two boilers are installed in a single setting 40 feet by 12 feet, on a flat at the after end of the engine room above the propulsion shafting.

Each boiler is fired by 3 Todd variable capacity mechanical-pressure atomizing oil burners arranged in a single vertical row. Each boiler has 4180 square feet of heating surgace; economizer heating surface 3024 square feet; air heater 2807 square feet, and superheater 1050 square feet. Each furnace has a volume of 1040 cubic feet. The boiler steam drum is 42 inches diameter and the water drum 30 inches diameter. The steam and water drums are in a vertical plane 16 feet center to center. Drums are of welded construction thereby eliminating butt straps. Furnaces are completely water cooled; closely spaced 2-inch tubes forming the sides, front, rear and roof. The refractory floor is placed over a network of water tubes carrying water from the lower drums to headers at bottom of the water walls.

During the heat flow the furnace gases first pass across the first bank of boiler heating surface which consists of three rows of widely spaced tubes, thence through a convection superheater of the horizontal bare tube, self-draining "U" bend type, composed of 1¼-inch tubes. After leaving the superheater the gases enter the last bank of boiler heating surface near the top and pass downward through 14 rows of 1¼-inch tubes. In leaving the bottom of the boiler the gases then turn upward and pass through the economizer and air heater to the stack. Stack temperatures average about 250 to 275 degrees F.

The economizer is of the extended surface, marine type composed of 2-inch seamless steel "U" bend tubes fitted with cast iron grill rings which gives the elements many times the surface of the bare tubes. The air heater, in which final heat recovery is made, is composed of 2-inch tubes 9 feet long, and arranged horizontally in 2 passes with the air inside the tubes. With this type of boiler overall operating efficiencies of better than 88 per cent are obtained.

Electricity for light and power is generated by two 300-kilowatt, 3-wire, compound wound, 120/240-volt direct current Crocker-Wheeler generators driven by De Laval geared turbines. Steam conditions for these units are 440 pounds pressure and 740 degrees F. total temperature, with 28.5 inches vacuum. Worthington auxiliary condensers, each with 445 square feet of cooling surface, are installed individually for each generator turbine. A dead-front type main switchboard is provided for distribution of current.

For emergency purposes there is provided a 7.5-kilowatt, 120-volt d.c. generator driven by Hill Diesel engine.

The feedwater heating system consists of a Davis "Paracoil" feedwater heater drain cooler with a capacity of 5700 pounds per hour from 183 degrees F. to 110 degrees F. and feed capacity of 64,000 pounds per hour from 92 degrees F. to 98.5 degrees F. From this unit the condensate passes a "Paracoil" first-stage heater having a capacity of 64,000 pounds per hour, and raises the temperature to 168 degrees F. using exhaust steam at 8 pounds absolute. Thence it passes through a Worthington deaerating heater with a capacity of 74,000 pounds per hour, raising the temperature to 240 degrees F. using bled steam from the high-pressure turbine at 25 pounds absolute. This heater has a surge capacity of 645 gallons. Thence to the third-stage "Paracoil" heater of 74,000 pounds per hour capacity where the feedwater temperature is raised to 310 degrees F. using steam at 100 pounds.

The main feed pump is a Worthington 4.5-inch × 8-inch vertical single-acting triplex plunger pump having a maximum capacity of 185 gallons per minute against a 575-pound pressure, and is driven by a Westinghouse 75-HP. motor. The auxiliary feed pump is a steam driven Worthington vertical simplex, 14 inches × 9 inches × 24 inches.

For fuel oil service there is provided one De Laval "IMO" transfer pump with a capacity of 225 GPM., driven by 15-HP. Westinghouse motor. There is also two De Laval fuel oil service pumps with a capacity of 116 GPM. each, Westinghouse motor driven, and one De Laval fuel oil service pump of 228 GPM. capacity driven by 15-HP. Westinghouse motor. For the handling of lubricating oil there is installed two De Laval "IMO" lube oil pumps of 325 GPM. capacity each, driven by 15-HP. Westinghouse motors. For lube oil cooling there is provided two "Paracoil" lubricating oil coolers with a capacity of 265 GPM. each from 130 degrees F. to 110 degrees F. In addition to the previously mentioned fuel oil service pumps there is also a 6-inch × 3-inch × 6-inch steam driven Worthington horizontal duplex stand-by fuel oil pump having a capacity of 13 GPM.

The propeller, furnished by the Doran Company, is a 4-bladed variable pitch solid manganese bronze propeller having a diameter of 21 feet 6 inches and a pitch of 21 feet 6 inches at 0.7 radius. It weighs 21.5 tons.

Worthington Pump and Machinery Corporation furnished most of the pumping equipment, the following Worthington units being installed:

Main circulating: Vertical centrifugal 12,000 GPM., 100 HP. motor.

Auxiliary circulating: Vertical centrifugal 1800 GPM. 16 HP. motor.

Main condensate: (2) Vertical 2-stage, 125 GPM., 16.8 HP. motors.

Auxiliary condensate: Vertical 2-stage, 30 GPM., 4.5 HP. motor.

Main feed: Vertical single-acting, triplex, 4½ inches × 8 inches, capacity 185 GPM., 69.5 HP. motor.

Auxiliary feed: Vertical simplex, 14 inches × 9 inches × 24 inches, capacity 185 GPM., steam driven.

Fuel oil service stand-by: H.D. 6 inches × 3 inches × 6 inches, 13 GPM.

Fire: Centrifugal, 3-inch, 2-stage, 400 GPM., 45.6 HP. motor.

Fire and general service: Vertical centrifugal, 3-inch, 400 GPM., 45.6 HP. Motor.

Clean ballast: Vertical centrifugal, 5-inch, 600 GPM., 12.2 HP. motor.

Bilge: Vertical centrifugal, 5-inch, 600 GPM., 12.2 HP. motor.

Dirty ballast: Vertical centrifugal, 5-inch, 600 GPM., 12.2 HP. motor.

Sanitary: Horizontal duplex, 2½ inches × 2 inches, 30 GPM., 2 HP. motor.

Drinking water: (2) Horizontal duplex, 1½ inches × 2 inches, 6 GPM., ½ HP. motors.

Port feed: Vertical simplex, 11 inches × 7 inches × 24 inches, 120 GPM., steam driven.

Evaporator contaminated feed: Horizontal duplex, 3 inches × 2¾ inches × 3 inches, 20 GPM., steam driven.

Evaporator make-up feed: Horizontal duplex, 3 inches × 2¾ inches × 3 inches, 20 GPM., steam driven.

Evaporator salt water feed: Horizontal duplex, 3 inches × 2¾ inches × 3 inches, 20 GPM., steam driven.

In addition to the foregoing, Worthington Pump and Machinery Corporation also furnished one 6-inch × 5-inch × 5-inch angle type, 2-stage, air-cooled main air compressor with a capacity of 66 cubic feet of air per minute discharging at 110 pounds pressure; also one emergency air compressor 3⅛ inches × 3 inches, vertical single-stage, air cooled, with a capacity of 6 cubic feet of air per minute.

All motor driven pumps and air compressors are powered with Westinghouse motors.

The official trials of the *Sea Arrow* were held off the California coast between Point Reyes and Santa Cruz on June 26 and 27.

During the trial period the vessel had all double bottom and deep tanks full. This condition, together with approximately 920 tons of ballast in No. 5 hold, gave the vessel a displacement of approximately 10,390 tons or close to 59 per cent of her full load displacement.

Despite adverse weather conditions, the vessel was subjected to an eight-hour endurance and fuel economy test, the first two hours at 9211 shaft horsepower followed by six hours at 8550 shaft horsepower, which is slightly over her normal designed power.

The maximum speed attained during the trials was slightly better than 19 knots, and preliminary calculations indicate a fuel rate for all purposes of .578 pound per shaft horsepower hour.

All contractual requirements were fully met by the vessel, including successful completion of the following tests:

Anchor gear test, emergency steering gear test, Z-maneuver, ahead steering test, turning circles, emergency astern (head reach), astern power ½-hour duration, astern steering test, emergency ahead (stern reach), and emergency circulation system test.

SHIPBUILDING ON A PRODUCTION BASIS.

This article by A. J. Grassick, General Manager, Ingalls Shipbuilding Corporation, Pascagoula, Mississippi, first appeared in the July 8, 1940 issue of "Steel" and was reprinted in the September 1940 issue of The Welding Journal, the Journal of the American Welding Society published in Easton, Pa., the cuts being loaned by "Steel." The following is reprinted from The Welding Journal.

About 112 miles east of New Orleans is one of the most unusual shipbuilding plants in existence, that of the Ingalls Shipbuilding Corp. at Pascagoula, Miss., occupying some 46 acres with 3000 feet of waterfront. Here the time-honored method of assembly by riveting has been abandoned entirely and all joints are arc welded.

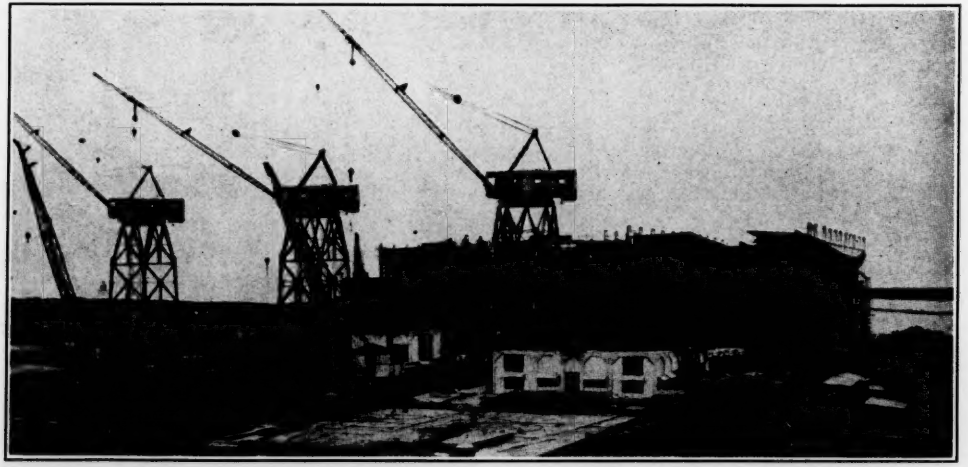
The shipyard has been designed primarily and essentially as an erection plant, depending to the fullest extent on the extensive fabricating facilities of the Ingalls Iron Works Co. at Birmingham, of which the Ingalls Shipbuilding Corp. is a wholly owned subsidiary.

In making all-welded ships at Pascagoula, existing facilities and organizations familiar with the fabrication of steel and installation of marine piping, electrical equipment, ventilation, joiner work, etc., have been used as far as possible. Another primary objective was to keep capital investment to a minimum.

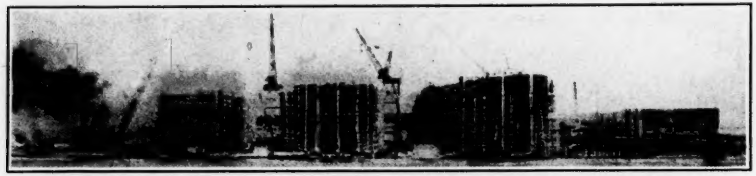
The shipyard is intended for the exclusive building of all-welded ships. This necessitated in many instances special types of tools, equipment, platen handling facilities, crane capacities, etc. The site was acquired in 1938 and the company's barge-building equipment at Mobile moved to it in January 1939. During the early part of that year, some 20 hulls were built and launched. The success of the planning of the complete plant is evidenced by the rapid and orderly progress being made on the fabrication and erection of eight single-screw C-3 cargo ships now being completed for the Maritime commission.

One of the first buildings to be erected when the plant was begun early in 1939 was the mold loft, a two-story structure, the ground floor of which has ample space for plate and shape storage and also a series of tables for the laying-out department. This space is served by a 15-ton bridge crane.

At right angles to the mold loft building and attached directly to it is the plate and angle shop. This is served by overhead cranes and a standard-gage gasoline locomotive. It houses an assembly platen 150 feet long and 35 feet wide and contains the heavy machine-tool equipment located for proper sequence of operation. The tools consist of a trim shear, gate shear, 30-foot plate rolls and an angle shear. There is no punching equipment whatever.



General View of Building Ways from Land Side Showing Structural Erection and General Platen Assembly Area. Comparatively Large Subassemblies Are Put Together on the Big Platens Where a Total Area of Approximately 23,000 Square Feet Is Available for This Work.



Stern View of Four C-3 Vessels Under Construction as Seen From the River. Note Towering Gantry Cranes, Big Enough to Handle Subassemblies Weighing Up to 75 Tons.

Tables for oxyacetylene shape cutting are quite extensive, as plate edge preparation for welding is an important factor in this work. Most plate edges are beveled.

A furnace and forge shop, 100 × 100 feet, built parallel and connecting with the mold loft at a right angle to the fabricating shop provides for a most compact and satisfactory arrangement of furnace blocks with an area 50 × 50 feet. Furnace equipment consists of 50-foot oil-fired angle furnace and a 35 × 10-foot plate furnace. Located at one side of the furnace blocks is a 500-ton hydraulically operated keel bender, capable of handling plates up to 25 feet in length. The furnace area is served by an electrically operated bridge crane, also is equipped with air and electrically operated winches and hydraulically operated bulldozers to facilitate the working of heavy materials at this location. All machines throughout these shops are served by jib cranes equipped with electric hoists capable of handling loads up to and including 5 tons.

A nearby building houses a 100-kilowatt converter and an electrically driven 500-cubic feet per minute compressor, delivering air at 100 pounds per square inch. The head of No. 3 ways houses two air compressors rated 850 cubic feet per minute to give a total capacity of 2200 cubic feet per minute available for the plant. Power at 2300 volts is transmitted to principal substations where it is reduced to 440 volts. Capacitors are used to give an average power factor of 95 per cent, insuring good economy.

At the end of the fabricating shop and running parallel to the mold loft is a finished material crane runway some 625 feet long and 77 feet wide. This provides storage for fabricated material received from the shops in Birmingham. An assembly platen, 72 × 72 feet, at the top end of this runway provides for the assembly of units weighing up to 18 tons. Entire area is served by two bridge cranes of 15- and 10-ton capacities, respectively. Heavy tool equipment in this area consists of a shape squeezer used for the cambering of beams, etc., and a plate joggler.

The original design of the shipyard contemplated five building ways. Ways Nos. 1 and 2 were completed July 1, 1939, and are of reinforced concrete construction built in a series of horizontal steps to a declivity of ⅝ inch per foot. Building No. 3 of the same design was completed August 1, 1939; No. 4, August 15, 1939. No. 5 has been projected and designed for future requirements. There is ample space along the remaining broad waterfront of some 2000 feet for additional ways.

Outboard launching ways were carried overboard to a depth of 8 feet at mean low water by construction of a steel cofferdam of interlocking piling. The entire river in the general vicinity of the launching ways has been dredged to a depth of 30 feet mean low water, ample for launching operations.

Building ways are served by three gantry cranes, each with a lifting capacity of 35 tons at a radius of 57 feet and towering nearly 200 feet in the air. (See accompanying illustrations.) When operated in tandem with an equalizing bar provided for the purpose, they are capable of handling weights up to and including 75 tons, such lifts being essential to the speedy and economical building of welded ships where comparatively large subassemblies must be lifted into place.

The three cranes are identical, are of the revolving type carried on a structural tower 65½ feet from track rail to roller path. Each tower is carried on four trucks of special design, two of which are power trucks, gear connected to 15-horsepower propelling motors and with automatic electrically operated brakes. Each tower is of the portal type, permitting passage of standard railroad equipment and locomotive cranes on railroad tracks on the center line of the gantry tracks. At the base, the gantry track is 20 feet from center to center of rails. The truck base is 30 feet.

The crane boom is 110 feet long with load line at 85 feet and the whip line at 110 feet. The 7-part load-line capacity for the crane at 57-foot radius is 35 tons and 13 tons at 95-foot radius while the 2-part whip line has a capacity of 6 tons at 35- to 100-foot radius.

Within the radius of these cranes are four large flat assembly platens with a total area of approximately 23,000 square feet, thus providing ideal conditions for assembly of weldments of maximum size.

Standard-gage railroad tracks passing beneath the gantry cranes and running the full length of each building slip make it possible to spot car shipments of fabricated steel, machinery and other material at any point desired. This permits material to be unloaded directly from car to ship, thereby saving expensive rehandling. This arrangement also allows the use of locomotive cranes, of which there are four for erecting and handling much of the material, thus definitely augmenting gantry-crane service.

Ample warehouse space is provided in a building 370 feet long and 45 feet wide with a mezzanine floor for storage of light material and a monorail for rapid handling of parts.

The building for the ship carpenter shop is 180 feet long and 50 feet wide and is equipped with surface planers, electric saws, heavy type band saw, jointer, grinders, drills, etc.

Machine shop, sheet metal shop and pipe shop occupy a building 212 feet long and 50 feet wide near the building ways and fitting-out docks. The paint department is in a nearby building, 70×30 feet.

The importance of proper facilities for rapid handling of materials at the fitting-out dock was recognized and is taken care of by a 50-ton stiff-legged derrick electrically operated and erected on a platform 65 feet above mean low water. The working radius will allow material to be placed on board in locations forward and aft of the midship deckhouse structure. Heavy lifts having been completed, vessels may be moved along the dock where they will be served by two 10-ton electrically operated derricks.

FABRICATING PROCEDURE.

The design of the fabricating shop and its heavy machine-tool equipment having been predicated on using the existing facilities of the Birmingham shops to the fullest extent, approximately 80 per cent of all mold-loft templets are shipped to Birmingham. Major portion of the work required to be furnaced, both plate and shape, and all plating requiring flanging, knuckling and rolling is done at Pascagoula where equipment has been installed for those purposes.

Successful, economical and rapid building of welded vessels requires that the entire structure be divided into subassemblies or weldments as large as existing crane facilities can handle. Practically all structural material with the possible exception of certain curved shell plating and framing finds its way into weldments passing over the assembly platens. The speed with which a welded ship can be erected depends largely upon the capacity of the platens. The six large plate-assembly platens here have a total area of approximately 34,000 square feet, ample space for these important operations.

In assembly of structural work on these platens, the use of liner-offs has been renewed. The lining-off on welded ships is made necessary because the mold loft produces no templets whatever for flat plating but instead issues a tabulation of plate sizes. All plating is received finished to exact size and entirely devoid of all datum lines. Platens are lined off for each assembly by liner-offs and the plating is assembled accordingly.

Inner bottom weldments consisting of assemblies made of inner bottom plating, vertical keel, floors, pipe tunnels and intercostals are assembled in an upside-down position, thus providing a maximum amount of down-hand welding. Such sections weigh up to 35 tons. All heating coils are installed prior to erection on the ship. All other weldments such as bulkheads, shaft alleys, side shell plating and decks are assembled with stiffener, beam and frame side up and completely welded manually while in this position.

Manual welding of subassemblies on the platens has the desirable advantage of permitting the joining of beam stiffeners and frames to proceed immediately after the plating has been assembled, thus making possible the continuous assembly of weldments without interruption.

Unionmelt automatic welding is applied extensively for all finish welding of seams and butts on all flat surfaces. Where possible this welding is completed on the ground prior to erection. However, where this is not convenient, the welding is completed after erection on the ship.

As prefabrication of assemblies reaches a point where a sufficient amount of material has accumulated, flat keels together with entire bottom shell plating are laid. Laying of the flat keel is immediately followed by erection of the entire flat portion of the bottom shell together with approximately 80 rolled plates. The regulating completed, this entire group of 80 plates is welded, prior to erection of inner-bottom assemblies, using the Unionmelt process. The erection of all inner-bottom weldments from the fore-peak to the after-peak bulkheads follows in rapid order to form a definite foundation for the remainder of the vessel.

Before the erection of an all-welded ship can be considered successful, it must have been erected at least as quickly as a riveted structure and, in view of the huge amount of ground assembly, should actually be erected in a somewhat shorter period of time. To accomplish this without the advantage of any erection holes whatever requires a great deal of preliminary planning as all conditions that might result in possible delays must be anticipated. That this is entirely possible is evidenced by the speed at which these vessels have been erected. Time for erecting principal steel work on a C-3 cargo ship is about the same as conventional methods would dictate.

Erection of the structure above the inner bottom is believed to be somewhat new and novel and certainly differs radically from accepted practice. As all of the lower side framing terminates at the inner-bottom margin plate and the underside of the third deck, thereby providing no means whatever of attachment to either of these structures, it was decided to erect on the inner bottom a substantial structure of shores and rib bands, carried up to the level of the third deck. The transverse and longitudinal bulkheads between the inner bottom and third deck having been erected, the deck assemblies next are placed in position on the shoring, thus automatically providing a means of attachment for the ground assemblies of the side-shell plating and framing.

While the inner-bottom plating amidship forms a natural support for the above-described system of shoring, difficulties were experienced at first toward the ends of the ship due to the rapid decrease in width of the inner bottom and the rapidly increasing flare of the side framing. Now, however, the outboard line of shoring is carried clear of the inner bottom and down to the concrete slab of the slipway itself, thus providing adequate support for the widely overhanging deck. This procedure is followed for each successive deck.

Shoring and erecting of materials for the extreme ends of the ship require special treatment. The elimination of the third deck at No. 5 cargo hold creates an extremely deep hole. A ground assembly of all-flanged plate girders, forming the cargo hatch of the second deck level, is made in a com-

plete assembly and erected as a single unit on the shoring provided for that purpose, thus enabling the erection of all framing and beams without difficulty.

In connection with their assembly, it was found helpful to introduce the almost forgotten steel hairpin, with which a sort of cradle is formed, thus supporting the upper ends of the frames, and to which the framing is tack welded in place.

In keeping with accepted practice, the cruiser stern is made the subject of a ground assembly with all members completely welded prior to its erection.

Exterior staging supports are entirely of steel construction, each upright constructed to form a ladder. These uprights require a minimum of space and reduce the fire hazard materially. The building of all-welded ships permits the entire system of staging to be considerably simplified due to the absence of heavy crafts such as reaming, bolting and riveting.

Single-operator direct-current welding machines predominate and are divided between 400- and 300-ampere units.

Unionmelt welding equipment consists of two machines of 1200-ampere capacity using a V-type welding head propelled on a traction carriage mounted on 6-foot lengths of track.

A 500-ampere, constant-current multiple-operator welding machine is provided for tack-welding operations in connection with assembly of work on the platens.

The entire absence of reaming, riveting and other noise-producing equipment results in a practically noiseless shipyard where it is possible to carry on a conversation without difficulty. The only exception is a relatively small number of chipping hammers found desirable for certain work.

During the construction period, the welded ship is almost entirely free from debris due to elimination of bolts, nuts, washers, rivets, coal ashes, etc. While this results in only a small reduction in cost, one considers the savings made possible by eliminating the cost of these bolts as well as handling, reclaiming and investment in the reclaiming plant itself, the savings over a period of time are considerable.

Small hand tools are of interest. Each structural worker is supplied with a small steel tool box containing a lightweight maul, hand hammer, steel heel wedges, pinch bar and push-and-pull jacks.

The eight C-3 welded cargo ships of 8500 gross tons each now being constructed in this yard represent over $20,000,000 worth of work. This is the first time in this country that a large shipyard had been built exclusively for the building of welded ships. The new yard is modern in every respect and represents a distinctly progressive step in shipbuilding methods.

THE SALVAGE OF H. M. S. *THETIS*.

The article which follows is abridged from a paper presented by G. R. Critchley to the Institution of Naval Architects. Reprinted from the July 19, 1940, issue of Engineering, published temporarily at Hayes, Middlesex, England. The method of salvaging H. M. S. *Thetis* differs radically from the method employed in salvaging U. S. S. *Squalus* described by Lieutenant Commander F. A. Tusler (C.C.), U. S. N., in the May, 1940, issue of the JOURNAL OF THE AMERICAN SOCIETY OF NAVAL ENGINEERS.

An account of the salvage operations requires the prefix that, although the Liverpool and Glasgow Salvage Association was entrusted with sole responsibility for, and control of, the operations as from June 9, 1939, the Association received vital assistance from naval deep-sea divers attached to

H. M. S. *Tedworth*, under the command of Lieut.-Commander W. J. Stride, R. N. These divers responded without hesitation to every requirement, often under conditions which would have justified some demur. Dr. A. M. Robb, the Association's technical adviser, supervised the adaptation of a merchant ship as a lifting unit, and calculated the stresses to which that vessel and the submarine would be subjected by the lifting operations. His calculations are used in the narrative.

The submarine was sunk in position 348 degrees 15 miles from Great Orme's Head Light, in a depth of 25 fathoms at low water spring tides. The average tidal range was found to be 22 feet, with a surface velocity reaching 4 knots. At times there was no period of slack water, and at best the slack-water period did not exceed 30 minutes. The position was exposed from all quarters, and the worst sea conditions could be expected with prevailing southwest through west to northwest winds. The Association's long experience supported the view that the ordinary type of dumb lifting camel used by harbor authorities for raising wrecks from navigable channels would be useless under these conditions, because even in moderately bad weather they would be completely unmanageable. This was demonstrated at the time of the Mersey Docks and Harbor Board's unsuccessful attempt on June 7. Under favorable conditions, the camels were pinned down at 9:30 P. M., but, with the incoming tide, conditions quickly deteriorated to moderate breeze and moderate swell, in which the camels rolled and labored heavily, and about midnight the after-wires successively parted and the forward wires had to be hurriedly slipped. The depth of water and the tidal velocity were both adverse to the work of divers. At the minimum depth of 25 fathoms, which involved divers working at a pressure of 66 pounds per square inch, sustained manual effort was impossible, and the tidal velocity would prevent divers descending, except during slack water. Divers cannot keep position in normal working depths, that is up to 80 feet, in a current of more than 2 knots. In shallower water, and dealing with a merchant ship, wires can generally be swept under the wreck. That method was useless, because there could be no certainty concerning the positions of the wires; the ballast keel of the submarine would obstruct a passage of wires along the bottom; there would be fouling of hydroplanes; and cutting of the wires owing to the form of the structure if they were slung at particular positions under the fore-end of the submarine. The divers were therefore essential to pass reeving wires and to check the positions of the lifting wires.

The decision to reject dumb lifting camels for use in this case led to the adaptation of a merchant ship as a lifting unit. The considerations affecting the choice of such a ship were that she should be of approximately equal length to the submarine; that her deck plan should permit us to arrange eight lifting beams athwartships, spaced so as to be approximately vertical to selected positions along the length of the submarine, so that as the submarine was carried into shallower water, and brought up closer to the lifting unit, none of the wires should assume a very acute angle; and that the four forward and four after beams should be capable of symmetrical distribution before and abaft the center of buoyancy of the lifting unit, so that she would not materially alter trim under the load. She should have generous ballast tanks so as to preserve stability with the heavy beams and other salvage gear placed on deck; she should not fine too rapidly at the ends, because the method would necessitate the transfer of the load from the decks to the tank tops through struts erected in the holds; and the greatest possible breadth at the ends was desirable for a wide distribution over the tank tops, because a narrow tank top would have involved excessive concentration of the load and an excessive slope of the struts. It was also necessary that the

lifting unit should have space for the fitting of sleeping and feeding accommodation for a salvage party of about fifty men, in addition to the navigating personnel, so that the whole unit could be self-contained.

The plans of numerous vessels were obtained and the *Zelo* was chosen. She was 308 feet long and 43 feet beam, in contrast with the submarine's length of 275 feet overall and 26 feet 6 inches beam overall. Her deadweight carrying capacity was 3350 tons, inclusive of 450 tons of bunkers, and the submerged weight of the submarine was said to be about 1000 tons. She had a total water-ballast capacity of 1036 tons, of which 73 tons was taken in ballast tanks on the port and starboard sides of the tunnel. Fresh water for boiler-feed and drinking could be carried in two tanks in the engine room. Her tons-per-inch immersion between the ballast condition and the contemplated loaded condition was 35, and thus only a small part of the rise of tide was lost by the mean sinkage of the lifting unit.

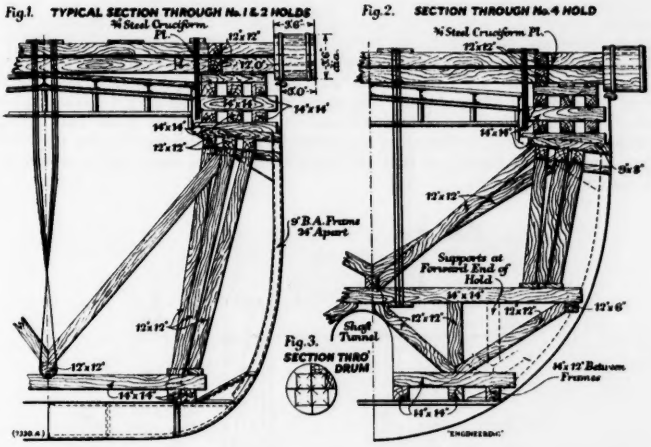
It was considered desirable to use eight slings, each of 9-inch wire. The nominal breaking strain of wire of that size, which is constructed of six strands, each of 61 wires of best quality galvanized steel laid clockwise around a hemp core, is about 240 tons. Twelve wires, each 120 fathoms long, four to be held in reserve in case of breakage, were constructed and delivered by the Rutherglen Works of Messrs. British Ropes, Limited, in the record time of twelve days, and were tested to a breaking strain of 265 tons. That gave a factor of safety of four in the wires, assuming uniform loading, and may seem, *prima facie*, to be the reverse of normal practice, which aims at a greater margin of safety in the means of attachment than in the wires themselves; but it was assumed that ten lifts would be required to take the submarine into shoal water, and that there would be considerable chafing and consequent weakening of the wires.

The athwartship lifting beams on the deck of the *Zelo* were each constructed of four square pitchpine logs, the ends of which overhung the deck on each side 3 feet, and were formed into bobbins by means of beech segments laid over the outer surfaces of three of the logs, and by greenheart segments laid over the outer surfaces of the fourth log in an order which met the condition that the wires would be taken round the bobbins and would be belayed in the clockwise direction, coming up on the after-sides of the beams on the starboard side, and on the fore-sides of the beams on the port side. This clockwise winding of the wires conformed with the clockwise lay of the strands. The greenheart segment formed the top quarter-circle of the bobbin, with which the lifting wire made contact as it entered upon its first turn, and the soft beech segments were used to permit the wires to bite into them to increase frictional resistance to slipping.

Figures 1, 2 and 3 show details of the lifting beams and under-deck stiffening. It was considered desirable to support the beams on grillages with soft wood packing, such as is used in the construction of fore poppets, in an endeavor to distribute the load over the portions of deck between bulwarks and hatch coamings on the lifting vessel. The effect of the packing and the consequent indeterminate distribution of support was that the exact magnitude of the bending moment was not known. Moreover, it was considered necessary to reinforce the beams by fitting wire ties secured around cross-beams on the inner bottom of the ship. As the tension in the wires was not known, another indeterminate element was introduced. It was possible, however, to determine the limiting values of the bending moment. In the result, there was a fairly wide range of possible bending moment, but not a very wide range of possible beams to resist this moment. Thirty-two pitchpine logs, ranging from 12 inches square to 16 inches square, were arranged in the groups of four, with the larger logs placed nearer amidships in the

lifting vessel, because it was expected that the loads there would be greater. With such an arrangement the stresses due to bending moment were not large.

Consideration of the resistance to twisting moment was more difficult. On an ordinary approximation to the strength of the rectangular section, and on the assumption that in each beam the four logs acted independently, the stresses were high. A cruciform ¾-inch steel plate was therefore interposed between the four grouped logs at each end of each beam, extending completely over the region of support, and the ends of the beams were bound together when the bobbins were formed. Further, in way of the hatch coamings, they were buttressed by fore and aft logs fitted between the beams, and from the end beams down to supports on the deck. It was not possible to arrange similar buttresses near to the outboard ends of the beams because this would have impinged upon the working space. Figure 4 shows the arrangement of the beams on the fore deck of the lifting vessel. The disposition of the stiffening was governed in part by the desire to tie the beams at the mid-lengths, which explains the arrangement of cross-beams and diagonal struts.



The Association's experience was that, with three complete turns of a 9-inch wire round each bobbin, the free end of the wire could be held by a light tackle with a pull of less than one ton. The method of "pinning down" at low water was to heave up the 9-inch wire on each side of the lifting craft with the ship's derricks and winches; when the wires had been hove to maximum tautness, they were secured at a point immediately below the bobbins by clamps, and the free ends worked round the bobbins.

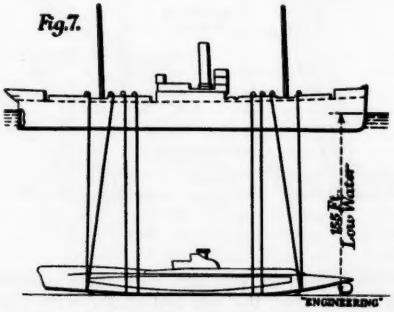
It became necessary to consider the strength of the hull of the submarine to withstand the stresses imposed by the contemplated method of positioning the wires. The salvage officer in charge at that time desired approval of the positioning of four wires just forward of the fore end of the ballast keel, and four wires abaft the keel, with a view to eliminating the difficulty of

placing wires under the keel, avoiding the risk of cutting them by the sharp edges of the keel, and avoiding damage by the wires to the external ballast tanks. It was known that, by this method, the slings would be about 188 feet apart.

Dr. Robb advised that, assuming that the whole weight of 1000 tons was uniformly distributed over this length of 188 feet, the bending moment would be 23,500 tons feet; and, alternatively, that, assuming that 90 per cent of the weight was thus uniformly distributed, and the remaining 10 per cent acted at 20 feet beyond each sling, there would be a bending moment of 20,150 tons feet. On the first assumption, the tensile stress on the material of the pressure hull would be about 15.3 tons per square inch, and on the second, about 13.1 tons per square inch; and, in his view, these stress figures were not so high as to render the proposed method inadmissible.

A concentration of four wires upon a small area in way of the spaces which were vital for the purpose of evidence might have cut through the pressure hull, or caused disturbance, which would have defeated one of the objects for which the salvage operations were undertaken, and accordingly an interview was sought with Sir Stanley Goodall, the Director of Naval Construction. He concurred in Dr. Robb's estimated stresses on the assumption that the submarine was completely flooded fore and aft, disregarding possible airlocks. If, however, one or more of the main compartments remained watertight, the pressure hull in that neighborhood would be subjected to stresses due to the depth of water which would perhaps be as much as 8 tons per square inch, and in that case the total stress would be of the order of 17 tons to 20 tons per square inch, and might have serious effect. The result of the discussion was that we agreed to place two lifting wires under the keel forward of the conning tower and two under the keel abaft the conning tower, so that the positioning of the eight wires would be as shown in Figure 7.

Fig.7.



The precise direction in which the submarine was heading was found to be S. 80 E., with a list of 15 degrees to 20 degrees to starboard. The ground was found to be blue clay, with a mound on the port bow, and a hole about 8 feet deep on the starboard bow. The keel at the fore end was slightly off the ground, but the stern had settled into the bottom up to the level of the starboard propeller boss.

The *Zelo* was ready to sail on June 28, but, owing to a southerly gale, did not sail until the evening of June 30. Conditions were still unsettled, and there was a critical interim stage between the time when she could be

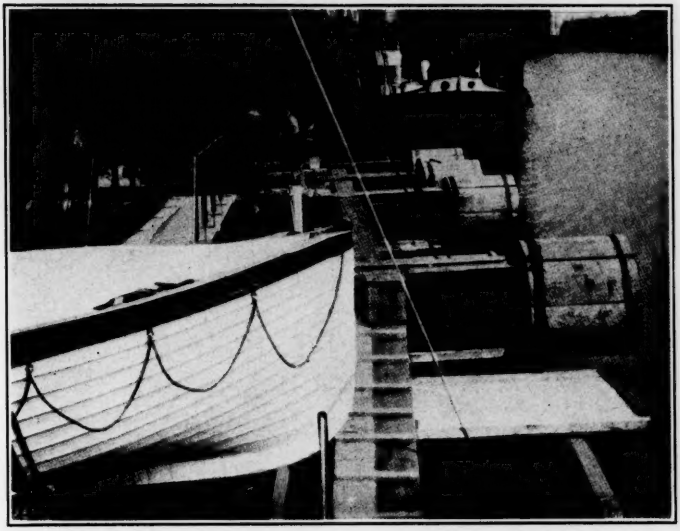


FIGURE 4.—BEAMS ON DECK OF LIFTING VESSEL.

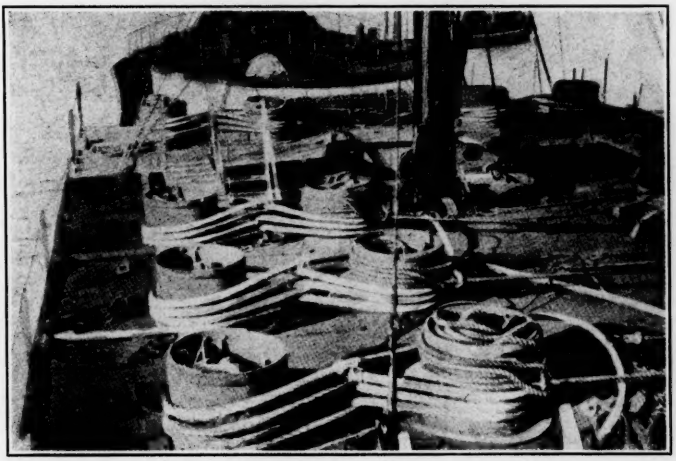
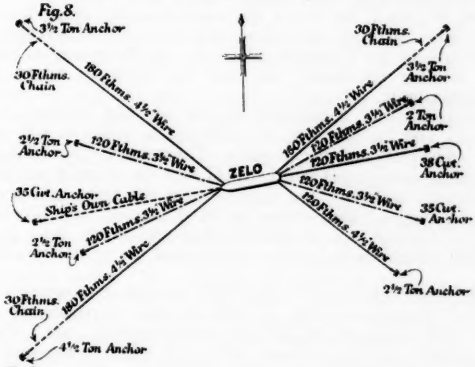
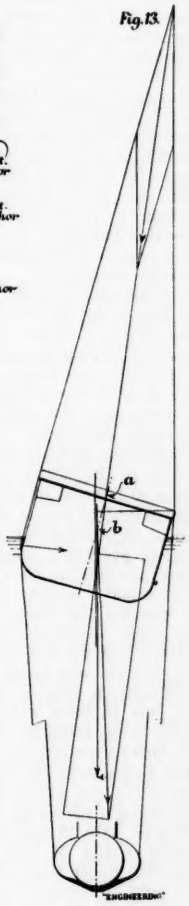
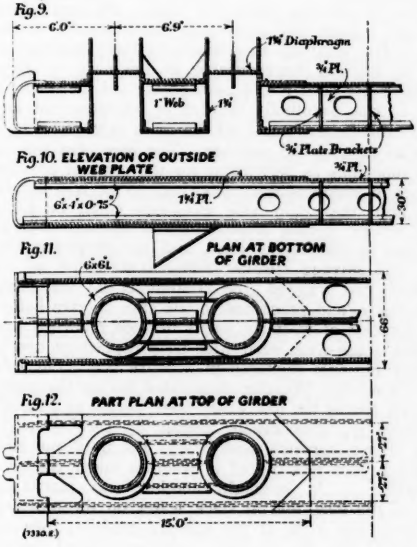


FIGURE 6.—ARRANGEMENT OF LIFTING WIRES ON BOLLARDS.

THE SALVAGE OF H.M.S. "THETIS."







placed over the wreck and heavy ground moorings laid out from the four quarters as well as from ahead and astern. It was not until July 4 that she could be moored in position. Weather prevented divers descending until the morning of July 6, when reeving wires were passed under the submarine's bow immediately forward of the keel. On that night, the weather rapidly deteriorated and became a whole south-westerly gale with heavy sea, and in the early hours of July 7, the *Zelo's* starboard moorings dragged and she broadsided to the gale, carrying away two heavy bollards and fracturing the bases of other bollards on the forecastle and poop. As there was no sign of improvement of weather conditions, she was instructed to return to Messrs. Cammell Laird's basin.

As large-scale charts showed unevenness of the sea bed between the position of the casualty and the east side of Anglesey, to which it was intended to carry the submarine, and the presence of wrecks in these waters was also known, a course was plotted which would give the clearest possible path during the movements inshore. The Controller of the Navy was good enough to place at our disposal the services of H.M. survey ship *Gleaner* for this purpose. The *Gleaner* also ascertained that sub-surface tidal currents ran in a direction sometimes as much as 60 degrees divergent from the surface current.

While new bollards were being fitted to the *Zelo,* consideration was given to improving the heavy ground moorings in order to avert a recurrence of the dragging which had occurred during the south-westerly gale. Our practice of rigging ground moorings to heave off a ship which is aground is to shackle the heaving wires to manilla purchases which are laid along the deck of the stranded vessel. These act as springs which absorb shocks coming upon the moorings in bad weather, in addition to their function as heaving appliances. That device was impracticable in the case of *Zelo,* because the purchases laid along her deck would have obstructed the manipulation of the lifting wires. It was eventually decided to interpose not less than 30 fathoms of stud-link cable between each of the main salvage anchors and wires, to act as springs in case of bad weather. The new plan was to adopt the chain-cable spring moorings as permanent for the original position and to provide a complete set of supplementary moorings to be laid in any new position to hold *Zelo* until the chain-cable moorings could be lifted and relaid. A plan of the revised system of moorings is given in Figure 8 showing the chain moorings in continuous lines, and the supplementary moorings in dotted lines. The salvage steamer *Ranger* remained at the case lifting the moorings which had dragged. By continuous day and night work, *Zelo* was again made ready, and proceeded to the case shortly before midnight on July 11, but a forecast of westerly winds delayed mooring, and on July 13 there was a strong south-west wind with no prospects of operations being resumed. On July 14, *Zelo* sheltered in Moelfre Bay. On July 15, there were strong northerly winds. Weather moderated during the night, and divers were able to descend during the low water slack period at 5 A. M. on July 16. There was, however, considerable trouble by reeving wires becoming foul owing to the strong currents, and it was not until the evening of July 18 that one lifting wire was placed in position under the propeller shafts of the submarine. At midnight another was placed in position under the fore end of the keel, and at slack water on the morning of July 19 another lifting wire was rove at the selected position forward of the keel. By the afternoon of July 20, six wires had been placed, and it then became necessary to lift the stern of the submarine in order to place the remaining two lifting wires in position.

On the early morning tide of July 21, the stern of the submarine was lifted smoothly off the ground and one 9-inch wire was placed well below the keel; but the reeving wire for heaving into position the remaining lifting wire fouled, and at 3:05 A. M. a wireless message was received from the salvage officer reading:—"Will you concur our lifting with one wire below keel aft and three wires between keel and propellers?" Approval was given on the understanding that the three aftermost wires were placed, one under the propeller shafts adjacent to the stern tube, one forward of the embrasure plates, and one at the point of junction of the after end of the keel with the hull.

On the midnight tide of July 21, all the wires were hove taut, and a test was carried out for the purpose of determining that each wire could be hove straight through from one side of the submarine to the other. This test was to ensure that if, during the course of a complete bodily lift, any wire or series of wires carried away, they would reeve freely under the submarine and eliminate the risk of an unbalanced load coming upon one side only of the lifting craft. This test proved satisfactory. It was decided to make the first complete lift on the early morning tide of July 22, and at 7:15 P. M. on July 21 a start was made to take in slack wires; low water being at 9:40 P. M. Weather conditions at that time were ideal. At 1:30 A. M. on July 22, when, if all was well, the submarine should have been moving inshore, the author transmitted an inquiry to the Admiralty Liaison Officer at the case and received the following reply:—"Regret to report there has been no victory stop. In spite of excellent weather conditions severe strain possibly owing to light stern and heavy bows of *Thetis* caused No. 7 and No. 6 beams to collapse in that sequence stop."

The following facts emerged: What was thought to be a perfect pin was made at low water, and all the wires were examined so that the load, as far as could be judged, was being evenly distributed over all the wires. Some adjustment was made to Nos. 1, 6, and 7 wires, numbering in order from the forward end of *Zelo*, and these wires were rendered up to approximately 18 inches, to secure uniform loading. At that stage, about an hour after low water, all the wires were held. For some reason the load on No. 5 wire did not increase at the same rate as the load on Nos. 6 and 7 wires, and the load on No. 8 wire became released altogether. Our officer did not know what load he had on No. 5 wire, but it seemed to have a fair load, although it did not show signs of serious straining as did Nos. 6 and 7 wires. As the tide rose, Nos. 6 and 7 beams began to show signs of twisting, and the fibers of the beams began to yield.

Under those conditions the tackles holding the ends of the wires were continuously released by hand, and the wires rendered around the drum ends of the balks in a series of very severe jerks. A stage was reached where it was not safe for men to try any further regulation of the load, and at that stage the tackles holding the ends of the wires carried away. Our officer was satisfied that the stern of the submarine was raised a considerable height from the ground, and that the bow was raised intermittently from the bottom, and its full weight was applied to balks Nos. 6 and 7 with the result that the wires rendered until the bow again took the ground. These conditions were accompanied by the surging of the submarine ahead caused by the tide, and with each surge the bow made contact with the bottom, and during the momentary bearing of the full weight of the bow on the bottom and the resultant release of the load upon the wires, these wires slid in jerks up the inclined keel to a position farther aft of the bow. Increase of the mean draught of *Zelo* showed that she was carrying a load of between 900 tons and 975 tons, which subsequently proved to be the total submerged

weight of the submarine, and in our officer's opinion, about 75 per cent of that load was borne by balks Nos. 6 and 7, and 25 per cent by balks Nos. 1, 2, 3 and 4. The uneven loading of the after balks on the *Zelo* was attributed to No. 8 wire being fouled, probably by a forward hydroplane. As the load increased, it freed itself, and, in fact, streamed away towards the stern of the *Zelo,* with the consequence that it exercised no restraint upon the tipping of the submarine at the bow. It was supposed that No. 5 wire either fouled debris or was lying with a slight kink under the bottom, and when it became slack it was able to slip along the inclined keel towards the conning tower without taking any load.

As no means existed of retaining the lifting wires in their allotted positions, having regard to the strength of the tides and the impossibility of sending divers down to check the positions of the wires in the limited time available, it was decided to consider replacing the lifting balks with steel girders capable of withstanding concentrated loading. A conference called by the Controller of the Navy was held on July 27, and it was agreed that operations should be continued with the proposed steel girders.

A request was made that the Admiralty should provide a mooring vessel to assist the *Ranger* in raising and relaying all the heavy ground moorings to keep pace with the *Zelo* carrying the submarine inshore. In the course of a few days a design of steel beams with built-in bollards was produced, but the time for construction and fitting was estimated at six weeks. As that would have meant that operations would not have been resumed until the middle of September, representations were made for a simplification of the design, and detailed amendments were made; but Messrs. Cammell Laird and Company's yard was to be closed from August 5 to August 12. After a personal appeal to the managing director of Messrs. Cammell Laird and Company, holiday leave for the men required was suspended, and by continuous day and night work the *Zelo* was refitted and again proceeded to the case on the morning of August 24. This was a magnificent performance, and in the result the saving of time was probably vital to the success of the operations, because, in fact, lifting operations were completed by September 3, and the weather broke on September 10.

Figures 9 to 12, illustrate the steel beams with built-in bollards and a cast-steel bolster at each end, constructed with leads to the bollards to take the load over the deck edges of the lifting craft. It was decided that the bollards should be capable of withstanding a load greater than the breaking load of the 9-inch wires, and that they should be arranged so as to leave adequate working space in the center of the deck. The bollards were constructed from 1¼-inch plates, and plates of this thickness rolled to an outside diameter of 36 inches would be subject to a stress of rather more than 3 tons per square inch under the combination of the calculated bending and twisting moments of 2715 inch-tons and 3413 inch-tons, respectively.

The requirement that the bollards should be incorporated in the beams suggested the provision of a bottom plate as well as a normal base plate, the distance between the two being the depth of the lifting beam. As it was decided that 30 inches would be an adequate depth for the beam, the bollards were made five feet long. They were reinforced internally to resist the calculated crushing loads. The width of the base plate was determined by the need for the provision of adequate scarfs for the outer webs of the cross-beam, and the extensions of the base-plate at the center line of the bollard were arranged to provide attachments for a central web of the cross beam. A completed bollard was tested at Lloyd's Proving House at Netherton to a pull of 180 tons. There were two figures of eight on the bollard with one end of the wire secured to the standing end of the testing machine and the

other end secured to the travelling end. There was no sign of disturbance of either riveting or welding on examination of the bollard after the test.

The beam was adequately strong to resist the bending moment imposed by the vertical loads on the wires, and the bending moments in the horizontal plane set up by the wires leading off the center to the circumferences of the outer pins were resisted by struts fitted between the bollards and from the end bollards down to the deck. These struts served also as anchorages for the beams in the event of the submarine when slung touching the ground while the lifting vessel still had ahead motion, in which event there would be a tendency for the lifting beams to be dragged aft. As a precaution against the submarine acting as an anchor while the lifting ship was being drifted to leeward, the brackets shown in the illustrations were arranged below the bollards.

It had been estimated that under the original conditions the lifting ship had a fairly generous metacentric height, even with a load of about 1000 tons suspended from the beams on the upper deck. The steel beams, however, were much heavier than the timber beams, and it was considered proper to carry out an inclining experiment shortly before the ship sailed. This showed that, with the load slung from the beams, there would be a small positive metacentric height.

Figure 13 is a diagrammatic representation of the lifting vessel inclined with the submarine suspended below, *a* and *b* being, respectively, the virtual centers of gravity of the load when the vessel is upright and inclined. This shows that, although at a small angle the load would be freely suspended, and therefore would act as if it were concentrated at the ends of the beams, one wire would soon be constrained at the bilge. The effect of this constraint is shown by the diagram as resulting in a lowering of the effective center of gravity of the load. The diagram is based, however, on the assumption that the wires can render freely under the hull of the submarine. Experience in other cases indicates that rendering does not occur, and that, therefore, submarine and lifting ship virtually behave as a single unit, with the two portions rigidly connected. The main consideration is that both the diagram and the facts of experience show that the stability consideration does not present a serious problem; in fact when the submarine was slung off the bottom, the *Zelo* was perfectly stable. Timber balks were fitted above the turn of the bilge along each side of the lifting vessel, to prevent indentation of the ship's side by the wires in the event of heeling under the load.

When the *Zelo* returned to the scene of operations on August 24, weather conditions were ideal, and by August 26 she was moored over the wreck, and all ground moorings and the lifting wires Nos. 1, 2, 7, and 8, which had been left in position after the unsuccessful attempt on July 27, were picked up. There was still, however, the persistent trouble of wires becoming foul owing to the tides, but by the morning of August 28 all lifting wires were in position, and *Zelo* was pinned down at low water, 6:30 A. M. The submarine was lifted on the morning tide, and the first move inshore was successfully made. Further lifts were made on each succeeding tide until six lifts had been completed by 11:10 P. M. on August 30, when the submarine had been carried into 78 feet at low water and was in a position N. 40 degrees E. true, 2 miles from Moelfre Island. In that position it was necessary to remove the forward periscope to prevent fouling the bottom of the lifting craft; the after periscope having already been bent nearly horizontal at some earlier stage.

Two further full tidal lifts were made, and finally a half-tide lift, which carried the submarine into a position S. 33 E. true, eight cables from Moelfre

Island, where she lay in 37 feet of water at low water; that is to say, her conning-tower hatch was about 9 feet 6 inches, and her bridge casing about 3 feet 6 inches, below water. Figure 14 shows the successive positions after each lift, and the course taken. The course plotted by H. M. S. *Gleaner* is shown by parallel lines, and it will be seen that it was impossible to follow exactly the marked course because of drift caused by the tides.

After the second lift, and during the second movement inshore, the submarine became pinned against a sandbank and remained for three hours, but cleared the bank with the continuing rise of tide. The situation was an anxious one, with *Zelo* broadside to the strong tide, but the tugs were able to hold on. Grounding of the submarine in the course of the movements inshore must be regarded as merely incidental to the operations. A common misconception is that a move inshore is not begun until the sunken craft has been lifted a substantial distance from the bottom, or, in other words, until a late stage of the flood tide, but in fact the move begins as soon as the sunken craft is off the bottom, and then takes the form of a slow creep inshore on to higher ground until, with the turn of the tide to the ebb, the sunken craft settles again on the bottom and the lifting wires slacken. If the bottom shelves very gradually a greater distance can be covered in one tide than if the bottom shelves more steeply, and if the bottom is irregular so that a bank must be traversed, a movement may be short while the bank is being negotiated, but the height of the tidal lift will be the same, and therefore a greater distance can be covered on the succeeding tide after the sunken craft has been lifted over the bank. This is well illustrated by Figure 14, if the second movement is contrasted with the third. The lifting craft was steered starboard bow to the tide, and the speed over the ground was kept down generally to 1 knot, but if the submarine touched bottom controllability was lost, and the lifting craft fell broadside to the tide. The two ahead tugs had then to steam up into the tide broad off the starboard bow. On the occasion to which particular reference has been made the tugs were unable to keep position and fouled each other, causing some anxiety in case they should be compelled to cast off.

Figure 6 shows the arrangement of the wires around the bollards after pinning. After the ninth move inshore the operations passed into the final stage, which involved bringing the submarine to the surface by means of compressed air, but war had been declared; H. M. S. *Tedworth* was withdrawn, although two of her divers remained to assist the Association's own divers.

The plan was for divers to strongback the various hatches, except the engine-room hatch, for which was substituted a plate into which were fitted one 6-inch siphon pipe that would reach down to the engine-room platform, and one 2-inch flexible siphon pipe that could be lowered into a sump adjacent to the forward engine-room bulkhead. A group of three air-injection valves was also fitted into this plate, as well as three other air-injection valves, so that, as the water was lowered throughout the submarine abaft of No. 40 bulkhead, and a larger volume of air was required to maintain a full discharge through the siphon pipes, this additional volume could be provided by bringing into action as required any or all three valves to supplement the three grouped valves. Bouyancy had to be restored to the compartments forward of No. 40 bulkhead by compressed air, injected through a valve to be fitted in the torpedo hatch, which would blow out the water through the open No. 5 torpedo tube. Nos. 2, 3, 4, 5 and 6 external tanks on the port and starboard sides of the submarine were to be controlled by compressed air injected through valves to be fitted into the tops of the respective tanks, and the No. 1 main ballast tank, which

passed under the bow, was to be drained by compressed air injected through an air pipe clamped into one of the flooding holes. Each of the air-injection valves was controlled by a cock operated by divers, non-return valves being useless as they would not permit the compressed air to be released whenever this might be required.

This plan, although apparently straightforward, was so much hampered by the conditions that it could not be completed until October 23, when the vessel was refloated and taken stern first inshore to a position where the stern was practically high and dry at low water. The beach was sheltered from prevailing southwest and west winds, and partly sheltered from northwest, but, as if by malign perversity, the prevailing winds did not prevail; from September 10, when the weather broke, there were persistent strong northerly and north-easterly winds, accompanied by heavy swell and frequently rough seas, and, in fact, during the period of 68 days while the vessel lay on the beach there were only 21 days when work was possible, and on some of these days only for a few hours.

The report of the Public Tribunal has disclosed that 67 victims of the disaster had congregated in the engine room and 32 in the after crew space. It was necessary to remove the bodies from the engine room to enable divers to obtain access to the control room and mess room, in order to open bulkhead doors to permit free flow of compressed air and drainage of water abaft No. 40 bulkhead, as well as to perform other necessary preparatory work. It will be a consolation to any relative of the victims who may read this paper to know that no consideration of expediting the work of salving the vessel was allowed to interfere with the removal of the bodies with the greatest possible decorum and care for their preservation. This consideration was so strongly sustained that the work of evacuation, which commenced on September 7, was not completed until September 30.

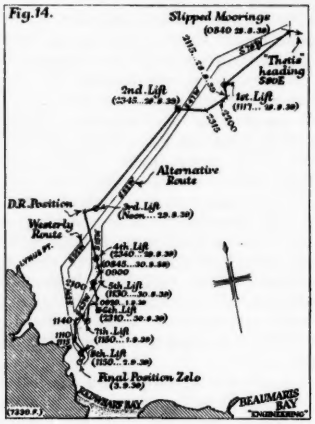
When divers were eventually able to obtain access to the control room it was found that air exhausting from the diving dresses was reaching the sea surface in way of the conning tower. It was presumed that there was leakage through the conning tower hatch, but investigation showed that the leakage was through the forward periscope, which had been broken off during the last stages of the lifting operations. This indicated leakage past the gland, and it became necessary to withdraw the cross head. After this had been done, and the bearing ring had been removed, a plug was inserted by divers into the forward periscope tube.

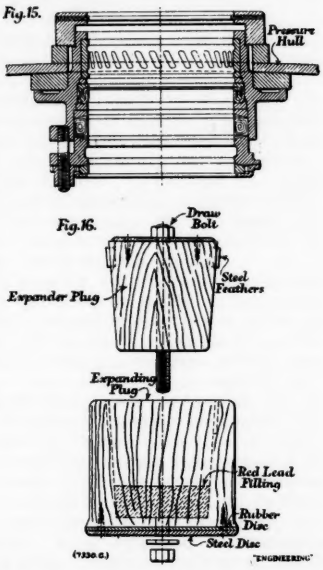
By October 11, everything was in readiness for a compressed air-test of the main body of the vessel, and at 10:33 A. M. blowing was commenced, but after 30 minutes a serious leakage developed in the vicinity of the conning tower. It was found that the leakage was coming through drain holes on the fore and after sides of the faucet in the forward periscope casting, but there were no signs of leakage elsewhere. Connections were made to additional air-injection valves in the plate over the engine-room hatch. Blowing was resumed the next day with increased volume and the 6-inch siphon pipe commenced to discharge water. After continuous blowing for six hours further air leakage occurred, which was found to be coming from the port main-engine exhaust pipe. This was plugged and blowing was resumed at 11 A. M. on October 13, but at about 4:40 P. M. air commenced to escape from the starboard main-engine exhaust pipe, and the siphon pipe stopped discharging water. The cause of the air finding its way through the engines was not understood at that time, but investigation of the construction of the engines, which were of two-stroke design, revealed that one of the pistons in each engine could be in a position where the inlet port and the exhaust port could be opened simultaneously, thus explaining the passage of the compressed

air. In these circumstances it became necessary to open up the engine-room hatch to enable divers to test the group exhaust valves. It was found that the port-engine group exhaust valve was half a turn open and the starboard engine valve two turns open, and these were closed. An investigation of the cause of the leakage through the forward periscope tubes showed that the plug had seated on the bottom of the gland and that both plug and gland were loose. It was deduced that the withdrawal of the periscope had disturbed the packing in the stuffing box above the gland and that air was escaping between the gland and the periscope tube.

Figure 15 is a diagram of the bottom section of the periscope tube, from which it will be seen why the tapered end of an ordinary plug allowed the escape of air between the gland and the periscope tube, given that the packing in the stuffing box had been disturbed. An expading plug was constructed, to reach up to the U leathers in the periscope tube and be sealed by expansion at its inner end against the neck ring of the stuffing box. Figure 16 is a diagram of the expanding plug.

THE SALVAGE OF H.M.S. "THETIS."





The fitting of this plug did not bring all the difficulties to an end. When divers descended on the afternoon of October 20, to make connections to the air-injection valves fitted to the after external tanks, it was found that these were buried in mud, that the stern of the submarine had settled in the mud during the periods of bad weather, and that the tail was just clear, from which it followed that the after hydroplanes were buried in approximately 6 feet of mud. On the following morning a diver was sent down with a

deck hose to try to clear the buried air cocks, but after an hour's work he failed to locate them. Blowing of the compartments forward of the No. 40 bulkhead and of the main body of the submarine, as well as of the Nos. 2, 3 and 4 port and starboard external tanks, was commenced, and was continued until the late afternoon, when the 2-inch siphon pipe commenced to exhaust air. A diver was then sent down and reported the No. 5 and No. 6 port and starboard air-injection valves clear above the mud. The submarine was maintained in a condition of just negative bouyancy during the ebb tide in the hope that the mud would be scoured from the stern. Blowing was resumed on October 22. Shortly after midday the bow surfaced and sank slowly, but after 30 minutes, during which blowing was continued, the bow again surfaced and remained. Air pressure was then released from the forward external tanks to permit the bow to settle again, as it was feared that with the strong flood tide it might be uncontrollable. Divers were again sent down and found the after hydroplanes and propellers clear of the mud, but a big volume of mud was held between the propeller shafts. As it was apparent that, with the trim of the submarine by the stern, a substantial body of water remained in the after crew space, a hole was drilled through the pressure hull below that space and an air compressor was kept running all night on the injection valves in the plate fitted over the engine-room hatch.

In the early morning of October 23, a diver reported that there was a good discharge through this hole, but a leakage of air was discovered from a pipe, 6 inches in diameter, adjacent to the No. 6 port external vent. This was presumed to be an overside discharge from a 100-ton pump, and was plugged. At 2 P. M. the stern came to the surface, blowing was commenced on the compartments forward of No. 40 bulkhead, and on the forward external tanks, and at 2:30 P. M. the bow surfaced with a 2 degree list to port. The submarine was then drawing 17 feet forward and 15 feet 3 inches aft, and was taken well up the beach stern first. Later the bow was hove inshore to a position where the open bow cap of the No. 5 torpedo tube was exposed at low water, the vessel was deodorized and made reasonably fit for entry by persons authorized to take evidence, and thereafter she was towed to Holyhead and drydocked. No damage of any significance had been caused by the salvage operations, and on November 18 we safely delivered her to her birthplace at Birkenhead.

MOTOR FUELS OF THE PRESENT AND FUTURE.

The following paper by Gustav Egloff, Director of Research, Universal Oil Products Company, Chicago, is reprinted from the April, 1940, Journal of the Western Society of Engineers, published at 1121 Dobson St., Evanston, Ill.

Introduction.

Today's research in the production of motor fuels results in tomorrow's high efficiency fuels for all purposes. Due to the programs of most nations which include national self-sufficiency, many heretofore practically untapped fuel sources are being utilized for national transportation. The limited supplies of petroleum in Germany have brought about the development of many types of synthetic motor fuels including gasolines from direct hydrogenation of coal, hydrogenation of carbon monoxide, and benzol from coal carbonization. Alcohols, both methyl and ethyl, have been used as blends with various hydrocarbon fuels, while compressed gases such as methane, ethane, pro-

pane, and butanes, and city gas, have come into use. Other developments along the line of substitute fuels have been the adoption and use of "producer gas" vehicles. Experiments with various non-hydrocarbon gases such as hydrogen and ammonia have been carried out. Acetylene, acetal, and coal dust have also been tried although, at present, there is very little use made of these latter compounds. Germany as the most efficient of "Ersatz" producers has succeeded in manufacturing about a third of her more than 60,000,000 barrels of oil requirement for 1939.

At the present time the quality most desirable for a motor fuel is a high octane rating which has been most economically possible when the fuel is derived from petroleum. Branched chain paraffins have, so far, proved to be the most satisfactory fuels both from an octane rating standpoint and from non-deteriorating qualities in storage and contact with air. These hydrocarbons are mainly used in aviation gasoline for transport, bombing, and pursuit planes.

Military airplanes in 1928 used gasoline of about 60 octane rating. In 1931 the Army aviation gasoline was 87 octane and airplane engines were developed to utilize this quality fuel which gave a 33 per cent increase in power per unit weight compared to 60 octane gasoline. In 1939 engines designed for using 100 octane gasoline yielded 25 per cent greater power output compared to 87 octane, while take-off distance was reduced 30 per cent and climbing speed increased 40 per cent. For transport planes, the advantages of 100 octane over 87 octane gasoline in a 1400-mile flight would be the dispensing of 1200 pounds of gasoline and carrying instead seven more passengers or their equivalent weight in mail or freight.

Leadership in 100 octane aviation gasoline with higher speeds and comfort of transport by airplanes rests in the United States. Aviation gasoline of this quality can be produced in the United States in sufficient quantity to supply the airplane needs of the world whether for civil or military use. A most significant factor in the development of 100 octane gasoline is that the overall efficiency of the airplane gasoline engine is about the same as that of the best Diesel airplane engine performance. One hundred octane fuel performance in airplane engines surpasses the Diesel in greater take-off and emergency power and flexibility in maneuvering.

Although 100 and higher octane gasolines are now used solely for airplanes, it will not be many years before the oil industry's researcher will produce them at a price level for use in passenger, truck, and bus vehicles and become sharply competitive with the best high-speed Diesel engines. There are many fuels which propel motor vehicles, however they are derived *primarily* from petroleum. Motor fuel from petroleum is made up of hundreds of hydrocarbons of the paraffin, olefin, aromatic, and naphthene series in widely varying percentages. Each hydrocarbon has a different velocity of combustion with knocking or non-knocking characteristics, hence only an over-all efficiency is obtained which is improving through the years. These complex mixtures are gradually being eliminated through perfecting the processes of thermal and catalytic cracking, and by the use of polymerization, isooctane, neohexane and alkylation processes.

During the past twelve years the octane rating of regular grade gasoline has increased from 50 to 73 which has meant over 20 per cent greater miles per gallon output for the 73 octane gasoline. Premium grade gasoline is now (1939) over 80 while in 1932 the octane rating of this grade was only 72. These striking increases in efficiency have meant huge savings to the motorist, while the price level has been lowered 7.5 cents per gallon in comparison with that of 1927 which means in terms of annual money saving to the motorist about $1,500,000,000.

Researches in the oil industry are tending toward the production of single hydrocarbons as gasoline in order that the combustion conditions of the modern motor may be controlled to a high degree of exactness. With the heterogenous mixture of hydrocarbons now in general use as gasoline, no comparable precision control under combustion conditions is possible. The motor fuel of the future as an ideal will be a single hydrocarbon or perhaps a blend of two or three hydrocarbons in order to suit the climatic conditions prevailing during the year with proper volatility and octane rating of over 100 for all types of motor vehicles.

A tremendous amount of research work has been carried out in the art of distilling crude oil with a precision undreamed of 20 years ago. Distillation units with capacities ranging from a few hundred to over sixty-five thousand barrels of crude oil per day have been developed to fractionate the gasoline present with such nicety that almost no further refining is required. The gasoline produced in the earlier days of distilling petroleum was treated with sulfuric acid and caustic soda and then redistilled to a commercial product. Today acid treatment is no longer necessary, for gasoline derived by distillation of crude requires, in general, no refinement beyond sweetening.

The antiknock value of straight-run gasoline varies widely, its octane number ranging from approximately 15 to over 70 (very little of the latter is available) and averaging about 53. This average value is too low for modern high-compression engines and the gasoline is in part reformed or cracked, i.e., the straight-chain paraffins which have low octane ratings are converted by heat and pressure or catalytically into olefinic, aromatic, and naphthenic hydrocarbons which have greater antiknock properties.

The thermal cracking of hydrocarbon oils, such as gasoline, naphtha, kerosene, gas oil, fuel oil, or crude oil, produces gasolines the octane numbers of which range to 75 with an average of about 68. The quality of the cracked gasoline depends upon the type of oil processed and the time, temperature, pressure, and principle of operation used. The catalytic cracking of oils produces a much higher octane gasoline than thermal, i.e., an average octane rating of 80.

The commercial methods used in producing motor fuel in the United States are extraction from natural and casing-head gas, distillation from crude oil, thermal and catalytic cracking of gasoline and heavy oils, polymerization of olefins in cracked gases, hydrogenation, and alkylation of a paraffin and olefin.

Distillation.

In atmospheric distillation, crude oil is subjected to fractionation in order to separate the gasoline (called straight-run gasoline) from the kerosene, gas oil, lubricating oil and wax fractions.

The crude oil is pumped through a series of heat exchangers counterflow to the hot vapors and liquids leaving the fractionating column, before passing to the heating coil distributed in the furnace. The temperature of the oil is raised to about 800 degrees F. as it leaves the end of the heating coil, while flowing into the bottom of the fractionating column. The products derived from this primary distillation are gasoline, naphtha, kerosene, furnace oil, fuel oil, wax distillate and bottoms.

The straight-run gasolines produced from Pennsylvania crude oil have octane ratings ranging from 35 to 50. With the exception of those obtained from White Castle, La., and Smackover, Ark. (octane ratings, 69 to 70), the straight-run gasolines have relatively low octane ratings. Yields range from 2.0 per cent for the crude oil from Placedo, Texas, to more than 81 per cent of 400 degrees F. endpoint gasoline from a crude in Medicine Bow, Wyo.

Cracked Gasoline.

straight-run gasolines and naphthas.

Thermal Reforming—In view of the increasing number of high-compression motors in use, straight-run gasoline is no longer suitable as a fuel. It is necessary to convert it into suitable hydrocarbons which possess greater antiknock properties. The branched-chain paraffins are considered the most desirable type *at this time;* olefins, naphthenes, and aromatics are suitable for motor car use but are not so suitable for airplane engines. To convert the knocking gasolines into non-knocking ones, they are subjected to temperatures of the order of 1025 degrees F. and pressures of the order of 750 pounds. It is estimated that over 25 per cent of the 259,000,000 barrels of straight-run gasoline and naphtha produced during 1939 was reformed (cracked) into gasoline of higher octane numbers. The reforming of gasoline is increasing in order to meet the demand for high-octane gasoline.

Catalytic Reforming—The catalytic reforming or cracking of gasolines or naphthas, in order to increase their octane rating is a relatively new development. In this process the gasoline or the naphtha boiling between 250 and 500 degrees F. is pumped to a vaporizer where it is heated to 850 degrees F., from which the vapors flow to the catalyst chambers. After passing through the catalyst chambers, heat exchanges, and fractionating tower, the products are separated into aviation gasoline, naphtha, gas oil, and gas. As the catalytic reaction continues, hydrocarbonaceous material builds up on the catalyst, which has to be burned off with controlled quantities of air. This regeneration of the catalyst calls for three catalyst towers, one of which is producing gasoline, the others in process of regeneration which takes place after each 10 minutes of operation, with 20 minutes allowed for regeneration each time.

The catalyst used is an active "hydrosilicate of alumina," which has a life of about 180 stream days or so. The operation of the catalytic unit is comparable with that of thermal cracking with the exception that the fuel requirement is lower.

Cracking Heavy Oils to Gasoline.

Thermal Cracking—The modern refining of crude oil, when only gasoline is the desired end-product, takes place in combination topping and cracking units. The yields of cracked gasoline, based upon the charge, ranged from 44 per cent to over 63 per cent with ratings from 68 to 77 octane number. It should be mentioned, however, that both the yield and the quality of the gasoline produced are dependent upon the cracking stock and upon such operating conditions as time, temperature, and pressure. Cracked gasoline is being produced at the rate of 293,000,000 barrels per year (1939) from charging stocks heavier than gasoline or naphthas.

Catalytic Cracking—The catalytic cracking of oil has been developed so that higher octane motor fuel can be produced than from high temperature-pressure cracking. A catalytic cracking test using a Mid-Continent gas oil yielded 85 per cent of 81 octane motor fuel. When the cracked gases from this operation are polymerized selectively and then hydrogenated, a yield of 12 per cent results, of a 96 octane rating motor fuel and comprised of branched-chain paraffin hydrocarbons (largely isooctanes) which are particularly suitable for airplane use. In addition to this yield of isoparaffins, 73 per cent of an 81 octane motor fuel resulted from the catalytic cracking of Mid-Continent gas oil. Such yields of high octane gasoline are not obtainable from the high temperature-pressure cracking of the same Mid-Conti-

nent gas oil. The process of catalytically cracking oil will profoundly influence automotive engine designers, as the speed and efficiencies of motor vehicles and airplanes will depend upon these types of gasoline.

The Houdry catalytic process produces an 80 octane motor fuel in 45 per cent yield on a once-through basis. A number of catalytic cracking units are now under design, construction, and operation in the United States.

Polymer Gasoline.

The production of gasoline from the waste hydrocarbon gases from crude oil cracking marked the beginning of a fairly definite knowledge of the chemical structure of motor fuels from this process. Polymerization of cracked gases yields gasolines of 81 octane rating by means of heat, pressure, and catalysis. The temperature required to carry on the process is about 450 degrees F., and the pressure is 200 pounds per square inch. Solid phosphoric acid is used as the catalyst. The reaction is exothermic, a temperature rise of about 150 degrees F. taking place in the catalyst bed. The polymer gasoline vapors pass through a cooling coil and thence to a receiver, gasoline being pumped to a stabilizer in order to produce a product of desired vapor pressure. The polymer product as produced has an octane rating of 80 to 83.

Analyses show that the vapor pressure of the raw polymer product ranged between 18.8 to 30.9 Reid vapor pressure. It is possible and generally advantageous to operate the poly plant stabilizer not only as a stabilization unit, but also as a means of effecting further butane recovery from the cracking plant gases. All of the butenes which enter the cracking plant stabilizer by deep stabilization can be made available for polymerization. As a result an increased yield of polymer gasoline is produced from the butenes normally contained in the 10 pound vapor pressure product. The recovery of additional butene from the gas discharged from the cracking plant stabilizer and poly feed is necessary to make up the deficiency in vapor pressure and gasoline volume brought about by polymerizing the butene contained in the cracked gasoline. The increased yield of polymer gasoline as a resultant of deep stabilization is from 40 to 50 per cent of that obtained when 10 pounds Reid vapor pressure cracked gasoline is produced at the stabilizer.

Isooctane Gasoline.

The butane-butene fractions from either the cracking or dehydrogenation process may be catalytically polymerized to yield isooctenes, and upon hydrogenation, yield isooctanes of 95 to 100 octane rating. The manufacture of isooctane requires temperatures of 250 to 350 degrees F. and approximately 750 pounds pressure with solid phosphoric acid as the catalyst.

Debutanization and rerunning of the polymers is carried out, and finally catalytic hydrogenation takes place to yield the aviation gasoline of 97 octane rating. A secondary polymerization stage operates on the unreacted normal butenes at a higher temperature (475 degrees F.) and low pressure (650 pounds) than the primary stage. The product from the secondary polymerization stage (non-selective) has an octane rating after hydrogenation of 85. After the polymerizing stage the liquid is run to the stabilizer where the unconverted butenes are separated and returned to the reactor.

The isooctene polymers are hydrogenated in the presence of a nickel oxide catalyst. The sulfur contained in the gases is removed before any treatment takes place, since the nickel catalyst is sensitive to sulfur compounds. The hydrogenation process operates at about 200 pounds per square inch pressure and the hydrogen and polymer product are supplied at this pressure. The temperature is maintained at 350 degrees F. during the reaction by the use of water-jacketing as for the polymerization step.

Catalytic Dehydrogenation of Gaseous Paraffins.

The development of catalytic dehydrogenation for the conversion of gaseous paraffins to olefins and hydrogen has made possible the utilization of paraffins from many sources as motor fuel.

Thermal cracking of paraffin gases is a competing source of olefins with the catalytic dehydrogenation method; however, catalytic dehydrogenation gives a better yield of the products desired and faster production than the thermal method. Catalytic dehydrogenation of propane, normal and isobutane is highly selective, yielding 85-95 per cent olefins from the paraffins. Side reactions are suppressed such as formation of methane, ethane, ethylene, and propene when processing butanes.

The catalysts for the reaction are oxides of the metals of the fourth, fifth, and sixth group of the periodic table, one of particular importance being chromium oxide on alumina. This catalyst is highly selective and converts the paraffin to the corresponding olefin in about 85 to 95 per cent of theoretical yields in an overall conversion. Hydrogen of 90 per cent purity is derived from this process also.

The dehydrogenation process is carried out by passing the butane charging stock through a heating coil in a furnace where it is brought to a temperature of 1020 degrees F. required to bring about conversion in the presence of the catalyst. The butanes are then passed from the heating coil to the reactors where dehydrogenation takes place in the presence of chromium oxide on alumina. Although the catalyst is not poisoned by sulfur compounds or carbon monoxide, the reactor material must not be of such type that it deposits iron oxides since they act as poisons for the catalyst. Carbonaceous materials which are deposited on the catalyst during the reaction of the butanes are removed periodically by heated oxygen containing gases which burn off the carbon deposit and thus reactivate the catalyst.

The products of catalytic dehydrogenation consist principally of normal and isobutenes, unconverted butanes, hydrogen, and a small amount of the lighter gases, methane, ethane, and ethylene, propane and propene. Continuous withdrawal to a cooler and compressor takes place during the dehydrogenation operation, where the liquefaction of butenes and butanes takes place. The gaseous fraction from the separator is passed to an absorber where any uncondensed butanes and butenes are separated by absorption from the gaseous fraction. The lighter gaseous fraction is rich in hydrogen (90 per cent) and is suitable for use in an isooctane making unit. The liquid fractions from the separator are supplied to suitable fractionating or stabilizing equipment where the dissolved light gases are removed. No further treatment is required before storage, or processing to liquid polymers with high antiknock value. Unconverted butanes are recycled to the reactors for further treatment.

Alkylated Gasolines.

There are two commercial alkylation processes for converting isobutane and olefins into branch chained paraffin hydrocarbons of high octane rating. They are the sulfuric acid and high temperature-pressure processes.

SULFURIC ACID CATALYST.

The sulfuric acid process for the production of high octane motor fuels operates on isobutane and aliphatic olefins. The olefins are absorbed by strong sulfuric acid at atmospheric temperatures and pressures; the reaction is relatively rapid and exothermic. Normal paraffins are not absorbed, but the isoparaffins are, if the sulfuric acid concentration is 90 per cent or higher.

It is thought that the olefin reacts to form an alkyl ester of sulfuric acid and then the ester reacts with the isoparaffin which must be added with the olefin, splitting out the sulfuric acid to form branched chained paraffins.

In actual practice the isoparaffin and sulfuric acid form an emulsion to which is added the olefin mixed with isoparaffin. Mixing of the components involved in the alkylation reaction is obtained by the use of a circulating pump and by the velocity of flow through baffles or jets.

The products from this process are especially suitable as aviation fuels due to the high octane number, high lead susceptibility, high-calorific value, and lack of sensitivity to different engine conditions.

THERMAL AND PRESSURE ALKYLATION.

Thermal alkylation may be accomplished by uniting hydrocarbons of the saturated and unsaturated type at temperatures of 950 degrees F. and at 3000 to 5000 pounds pressure. Alkylation of the thermal type is quite useful in the conversion of hydrocarbon gas into motor fuel since it operates readily on the lighter olefinmolecules such as ethylene and propylene which are not so reactive in sulfuric acid alkylation. The n-pentane, n-butane, and propane as well as the isoparaffins react with equal ease in thermal alkylation, and ethane may be cracked to form ethylene, and then enter into the reaction.

The neohexane process consists of thermally alkylating isobutane with ethylene. It is necessary that the feed stocks be of high purity and that the conversion per pass be relatively low. In order that the conversion per pass will be maintained at a low level the olefin to paraffin ratio is kept low which also prevents the polymerization of the olefins. Low concentrations of olefins are added during the reaction in order to effect continuous alkylation. The process consists of a two-step operation, the first being a cracking operation carried out on an ethane-propane mixture to produce ethylene, and the second step consisting of the alkylation of isobutane with ethylene under high pressure.

"The gaseous products are cooled, compressed, scrubbed with isobutane to remove light oils formed in cracking, and contacted with isobutane which absorbs the ethylene. The ethylene-isobutane mixture is pumped to a manifold which distributes it among 10 inlets situated along a tube coil which constitutes the reaction zone through which a separate stream of isobutane of greater volume is continuously pumped. A preheat coil imparts the desired reaction temperatures, about 950 degrees F., to the isobutane stream prior to its entry into the reaction zone, and this temperature, within the reaction zone, is maintained by a flow of hot combustion gases. Conversion pressures are in the range 3000-5000 pounds per square inch. The liquid products are separated from the reactor effluent by conventional fractionation."[1]

Secondary reactions produce other motor fuel hydrocarbons which are above the neohexane boiling range. The formation of tar is retarded and the alkylate is yellow in color.

Neohexane has an octane rating of about 94 as does the 2, 3-dimethylbutane. These hydrocarbons are in the antiknock range of isooctane, and due to the higher volatility as compared to isooctanes may be used to provide volatility flexibility in blends of high octane rating.

When running to motor fuel a higher conversion per pass may be used and in that way greater output of alkylate is obtained. This motor fuel requires less fractionation and refining and is suitable for blending although it is not as pure neohexane as that obtained by low conversions per pass.

[1] "Thermal Alkylation and Neohexane," G. G. Oberfell and F. E. Frey, Phillips Petroleum Co., American Petroleum Institute Meeting, Chicago, Ill., November, 1939.

Aviation Safety Fuels.

In addition to the individual hydrocarbons which are being developed for use as aviation fuels, a definite effort is being made to reduce the fire hazard from the airplane fuels.[2] High octane safety fuels tried have included completely paraffinic and almost completely aromatic types; the flash point has been about 110 degrees F. A gaseous or liquid fuel is required for starting but great precautions are necessary in handling since the added volatility means added danger from fire. Gasoline engines of 1500 HP. can be readily developed to run on this type fuel, and a further development might also be in the injection-type engine. The safety fuels of 100 octane rating so far developed have been completely aromatic in type running between 75 and 95 octane rating. These fuels are lower in calorific power than the paraffins and are less suitable due to lower octane ratings. Paraffinic safety fuels of 99 octane number are more suitable in lead response, heat content, and octane rating than the aromatics.

Safety fuels are being investigated[3] by commercial airlines and government agencies. Hydrogenated trimer (triisobutylene) may be utilized as a blending agent for such fuels in the same way that commercial isooctane is used for normal aviation gasoline. High boiling naphthas of the safety fuel type, and having unleaded octane numbers from 80 to 90 may be produced by hydrogenated feed stocks.

However, it should be stressed that pure compounds of required volatility should be investigated for safety fuel purposes.

Natural Gasoline.

Natural gasoline is an important part of our motor fuel supply, chiefly because of its high volatility, blending properties, and antiknock value, which ranges from 70 to 85 octane number having vapor pressures of 18 to 26. It is obtained from casinghead gas, which flows from oil wells along with the crude oil, and from gas-well gas. These gases contain hydrocarbons, such as methane, ethane, propane, butanes, pentanes, hexanes, heptanes, and octanes, from which natural gasoline may be fractionated.

The presence of natural gasoline was first discovered in the early 1880's, when many operators of natural-gas transportation systems experienced trouble with condensation in the lines. It was soon determined that this condensate was gasoline, and draw-off drips were installed in low places along the lines. At that time the facilities for collecting this so-called drip gasoline consisted in utilizing the normal gas line pressure with the addition of a few cooling coils.

Today, there are about seven hundred natural-gasoline plants in operation in the United States, with an estimated total daily capacity of over 5,700,000 gallons. The greatest natural gasoline-producing area of the United States lies in the Mid-Continent and Gulf Coast fields. The actual production in the United States during 1938 amounted to 2125 million gallons, or more than 9 per cent of the total United States motor fuel production.

When natural gasoline is the primary product desired from casinghead or gas-well gas, its separation from methane, ethane, and propane is much simpler than when individual components are the desired products. This separation may be accomplished by: (1) simple compression and stabiliza-

[2] Aviation Fuels—Present and Future Developments, S. D. Heron and H. A. Beatty, American Petroleum Institute Meeting, November, 1938, Chicago, Ill.

[3] E. V. Murphree, C. L. Brown, and E. J. Gohr, Petroleum Division, American Chemical Society, Baltimore, Md., April, 1939.

tion; (2) compression followed by absorption and fractionation, or absorption, distillation, and fractionation; (3) absorption in activated carbon followed by distillation and stabilization. This latter process is now largely superseded by the other processes mentioned.

The simplest method is that which utilizes compression of the gases followed by stabilization of the gasoline produced to the desired vapor pressure. The gas is compressed to 250 pounds per square inch, after which it is cooled to 75 degrees F., run to a surge tank for intermediate storage, and then to the stabilizer. The bottom portion of the stabilizer or fractionator is maintained at a temperature of 250 degrees F., while the top temperature is held at 110 degrees F. by recirculation of the liquid in the accumulator tank. The pressure is maintained at 225 pounds.

When producing natural gasoline from the various sources to three groups, it is obvious that considerable leeway must be allowed in octane rating and specific hydrocarbons present. It will be noted that as front-end volatility increases so does the octane rating. However, there are a few plants, principally in the Gulf Coast area, which produce a product of relatively low volatility but of high octane rating. Examination shows this to be due to the presence of aromatics, naphthenes, and certain branched-chain paraffins.

One of the principal constituents of natural gasoline is isopentane. It is estimated that by simple fractionation 190 million gallons of isopentane could be produced annually in the United States. Its high antiknock value (90 octane number), good susceptibility to tetraethyl lead, and low boiling point (82.3 degrees F.) make it an excellent blending agent for high-octane aircraft fuels.

In the production of 100 octane aircraft fuel, isopentane is generally blended with the main components, isooctane and straight-run gasoline, for the purpose of supplying the required front-end volatility. The amount of isopentane added is usually restricted to about 15 per cent, because of its relatively high vapor pressure.

Aviation Gasoline from Hydrocarbon Gases.

The potential polymer gasoline of 81 octane available from the ethylene, propene, and butenes on the assumption that it is all used for this purpose is at the yearly rate of 8,345,000,000 gallons.

The polymer gasoline of 82 octane from butenes may be used as motor fuel or blended with lower grade gasoline to enhance its octane rating. When aviation gasoline is the desired product the butenes present in cracked or dehydrogenated gases are selectively polymerized so as to produce isooctenes by the reaction of normal butene and isobutene in ratio of 1:1, which in turn is converted into isooctanes of 96 octane. The volume of 96 octane aviation gasoline potentially available from the butenes is over 2,180,000,000 gallons a year. The normal butene left over in the residue gas from the first polymerization reaction is subjected to polymerization in a second step which upon hydrogenation produces a saturated 85 octane aviation gasoline stock. The volume yearly potentially available of this product is 1,095,000,000 gallons.

A number of economic situations exist where it is more desirable to alkylate isobutane with ethylene, propene, or butenes than the combination processes of polymerizing and hydrogenation. It is estimated as an average that normal and isobutane are present in the ratio of 75 to 25 per cent. This means that there is potentially available about 35,500,000,000 cubic feet of isobutane.

The thermal alkylation of combining isobutane with ethylene at high temperature and pressure, producing neohexane of 94 octane rating, has a yearly potential production of 1,290,000,000 gallons on the assumption that all the isobutane available is used in this process.

The catalytic sulfuric acid alkylation process may use propene and butenes with isobutane to form alkylate. The volume of alkylate from propene and isobutene potentially available if all the isobutane were used would be 1,500,000,000 gallons of 85 octane rating. If butenes are used for alkylation with isobutane the yearly volume available of alkymer would be 1,715,000,000 gallons of 93 octane rating.

The following table shows the aviation gasoline potentially available from hydrocarbon gases.

Process	*Gallons*	*Octane No.*
Dehydrogenation, Polymerization	2,180,000,000	96
Hydrogenation	1,095,000,000	85
(From Butanes-Butenes-Hydrogen)	3,275,000,000	(avg.) 92
Thermal Alkylation (Neohexane)	1,290,000,000	94
(Isobutane and Ethylene) Sulfuric Acid Alkylation	1,715,000,000	93
(Isobutane and Butenes)		

Coal Hydrogenation.

Development of hydrogenation and other processes for deriving motor fuel by synthetic means has been encouraged by many of the nations that are lacking in petroleum resources. Germany and Great Britain have led the field so far in deriving liquid fuels from coal. At the present time (1939) France, Russia, Italy, and Japan are either finishing plants for commercial production or are experimenting in the field of fuel production.

Hydrogenation of coal for the purpose of manufacturing liquid fuels and lubricants has been developing since 1913 when Bergius first demonstrated the practicability of large scale hydrogenation. In 1927 industrial development of this process was started by I. G. Farbenindustrie whose independent research had discovered non-poisoning hydrogenation catalysts and both liquid and vapor phase methods of hydrogenation.

Due to the pressure in Great Britain to become less dependent upon imported motor fuels, and the great need of the coal mining industry to return to a normal business, the investigation of the Fuel Research station on the feasibility of hydrogenating the bituminous coals of England was begun in 1923. The Bergius process was used and by 1927 the process was of sufficient value to be taken over by the Imperial Chemical Industries.

In 1931 the four companies most interested in hydrogenation processes, I. G. Farbenindustrie, Standard Oil of New Jersey, Royal-Dutch Shell, and Imperial Chemical Industries formed a "pool" under the name of International Hydrogenation Patents, Ltd., for combining patent and technical information. Much research was carried on in various countries in order to determine the type of coals within the country and to test the feasibility of carrying on the hydrogenation processes with the various types.

In England boiler slacks have been found to be the most suitable for hydrogenation since the friable coal contained in them is the most easily hydrogenated. Hydrogenating processes are best operated in conjunction with the collieries since the raw materials will not require hauling and the larger sizes of coals produced may be sold as house fuels since the hydrogenation requires only pulverized material. Anthracite and steam coals are not suitable for hydrogenation. However, it has been found that all coals having a carbon

content or an ash and moisture-free basis of less than 87 per cent are amenable to hydrogenation. In order that as low an ash content as possible be obtained the coals are subjected to special cleaning.

The hydrogenation process operates on liquids and solids both in the liquid and vapor phase. In the United States the process was introduced in order that heavy oils might be made into the more valuable motor fuels, while in Germany and Great Britain coal was used and heavy oils from the hydrogenation were recycled to bring up their hydrogen content. The essential feature of the hydrogenation process, regardless of the material to which it is applied, is that hydrogen combines with coal, coal tar or oil by means of heat, pressure, and catalysts to form gasoline. When petroleum is used, the quality of product is greatly improved by hydrogenation.

COAL HYDROGENATION PROCESS.

In the hydrogenation of coal, the yield of motor fuel is about 60 per cent by weight, with octane ratings ranging from 71 to 75.

In the hydrogenation of coal to motor fuel the first beneficial stage is to clean the coal of mineral matter, which is accomplished by floating the raw coal upon a suspension of sand and water.

It has been found that injection of hydrogen chloride or hydrogen chloride-forming compounds during the hydrogenation of coal improves the reaction itself and the operating results by neutralizing the residual coal ash. Although hydrogen chloride is highly corrosive, this factor is overcome by pumping in an alkaline paste.

The hydrogen used in the commercial unit at Billingham, England, is produced from coke and steam and hydrocarbon gases produced from the hydrogenation process.

The process of hydrogenation may be applied to coal and oil mixtures, low- and high-temperature coal-tar mixtures, or to heavy oils from low- and high-temperature carbonization of coal, for the production of motor fuel. When coal is used, it is first mixed with heavy oils to form a paste which is pumped into the apparatus. Oil is produced when coal is in contact with hydrogen gas, at a pressure of about 250 atmospheres (atm.) and a temperature of 842 degrees F., in the presence of organic tin catalysts, molybdic sulfide or other catalysts. The hydrogenation process takes place in three stages. The first stage hydrogenated the coal paste, producing an oil, which is fractioned into motor fuel and middle and heavy oils. The heavy oil is hydrogenated in the liquid phase to motor fuel, while the middle oil is hydrogenated in the vapor phase to gasoline. The motor fuel produced is then refined to a finished product of 71 to 75 octane number. In this process, four tons of coal are required to produce one ton of gasoline.

The Billingham, England, coal-oil hydrogenation plant to produce 150,000 tons or 1,070,000 barrels of gasoline a year cost 5,500,000 pounds or about $27,000,000. It is stated that this is substantially more than would be required for an entirely new plant of similar output. Nearly 4000 tons of coal per day are required to operate this plant.

The ratio of four tons of coal to one ton of gasoline produced can be maintained in a new plant (even if coal is used without creosote or low-temperature tar), owing to the improved methods of hydrogen manufacture which would be employed.

When petroleum oils are hydrogenated, the principles involved are similar to those of the coal-oil mixture operation. The two oil hydrogenation units in operation in the United States are not used primarily to produce motor fuel, but to produce special oils such as solvents and lubricants.

CARBON MONOXIDE FROM COAL OR COKE HYDROGENATION.

The Fischer-Tropsch process for converting water gas into hydrocarbon oil, called Kogasin (named from kohle + gas + benzine), is in commercial use in Germany and France.

This process utilizes a mixture of hydrogen and carbon monoxide with cobalt, iron, or nickel as catalysts (without alkali) at a temperature of 392 degrees F. at atmospheric pressure. In the presence of strong alkali the polymerization continues until solid paraffins rather than liquids are produced. The theoretical yield of liquid hydrocarbons is 185 grams per cubic meter of gas containing 29.5 per cent carbon monoxide and 60 per cent hydrogen. A conversion of this water-gas mixture into 81.6 per cent of hydrocarbons may be obtained from a two-stage operation at 363-374 degrees F. using a cobalt-copper-thorium-kieselguhr catalyst. Water gas, containing 42 per cent carbon monoxide and 48 per cent hydrogen, gave a yield of 160 cubic centimeters of oil per cubic meter of water gas, using a nickel-manganese-aluminum oxide catalyst. On the basis of 40 pounds of coke required to produce 1000 cubic feet of water gas, this is equivalent to 56 U. S. gallons of liquid hydrocarbons per short ton of coke.

Kogasin is principally a mixture of straight-chain or slightly branched-chain saturated and unsaturated hydrocarbons containing: gasoline, 86-428 degrees F.; Diesel oil, 428-662 degrees F.; and wax. The gasoline fraction is water-white and sulfur-free. Fatty acids are present in small quantities and olefins to over 50 per cent.

The nature of the hydrocarbons in Kogasin depends upon the catalyst and water-gas mixture used, cobalt producing more unsaturated oils than nickel.

The water gas used for catalytic conversion to hydrocarbons is derived commercially from the reaction of steam upon coke or gases such as methane. A relatively high degree of purity of water gas is required, owing to the poisoning effect upon the catalyst of hydrogen sulfide and organic sulfur compounds. A water gas derived from coke and steam, having the composition of 6 per cent carbon dioxide, 40 per cent carbon monoxide, 50 per cent hydrogen, and 4 per cent nitrogen, methane, and oxygen, was reported by Martin as a commercial gas for catalytic conversion to hydrocarbons.

ALCOHOL MOTOR FUEL.

Ethyl alcohol is used in many countries for blending with gasoline motor fuel, and is derived mainly from fermentation of agricultural products such as beet sugar, molasses, potatoes, and corn. However, synthetic processes accounted for 10 per cent of the 120,000,000 gallons of ethyl alcohol produced from cracked gases during 1938.

Power alcohol was heavily subsidized by the Central European Powers from 1930 to 1937 in order to take care of the surplus argicultural products and to bring the alcohol industries up to a production level capable of supplying the munitions industries.

Power alcohol consumption in Europe increased during the period 1930 to 1936 from 59,000 to 648,000 tons. During 1937 a decline of 25 per cent brought the consumption to 510,000 tons with another heavy drop in 1938. The elimination of alcohol as a motor fuel is desirable, since the economic losses are great and the food supply is cut down due to the heavy drain on carbohydrate materials.

A loss of income of about $105,000,000 was incurred during 1937, from tax losses, higher fuel costs, and subsidizing the producers. In the same period alcohol accounted for only 4.3 per cent of the total amount of motor fuel requirements. Probably one of the worst aspects of the situation in con-

nection with required alcohol blends has been the constant shifting of the governmental requirement of alcohol in gasoline. As a consequence both the drivers and automobile manufacturers are constantly changing the adjustment of the carburetor in order to use the motor fuel on the market which may vary in alcohol content from zero to 20 per cent, depending upon crop failure or war preparation; and due to the shift in fuel, the efficiency of the engine is cut appreciably since any adjustment is as unstable as the fuel input of the motor.

Recent events have confirmed previous analyses showing that the primary reason for compulsory use of alcohol in motor fuel in Europe is the desire of the countries to develop and maintain their alcohol industries for the purpose of national defense; this is done not merely as a protection against failure of petroleum supplies in wartime due to blockades but particularly to assure adequate capacity in wartime for manufacture of a prime raw material in making munitions, namely alcohol. Significantly, the war scares which gripped all Europe during 1937 and 1938 were accompanied by a sharp decline of alcohol used in motor fuel. This decrease was far too great to be explainable solely by crop shortages in sugar beets, the main source of alcohol in France and Italy, and must be attributed to the large quantities of alcohol consumed for armament purposes. Classified as confidential military information, diversion of alcohol from motor-fuel channels to use in making munitions has seldom been publicly mentioned. In at least one instance, however, it has been reported as a cause for the decline in France of the use of alcohol in motor fuel during 1937. Numerous informed sources abroad privately acknowledge that similar diversion of alcohol is also an important factor for the decline of alcohol for use in motor fuel in Italy and probably in Germany.

Because of the natural inclination of foreign nations to avoid this sensitive topic, it is likely that the desire to maintain a vital wartime industry in a continuous condition which permits operations at peak capacity has been greatly understressed as a cause of Europe's compulsory use of alcohol in motor fuel. A realistic appraisal of the situation compels the conclusion that this consideration has been a basic incentive for Europe's power alcohol policies, possibly outweighing even the desire to overcome vulnerability to wartime failure of petroleum supplies due to blockade. At times incapable of meeting all requirements in peace time, as in 1937, most European nations clearly do not have alcohol industries of sufficient capacities to meet motor-fuel needs and wartime scale of munitions manufacture simultaneously. Indications are that at least one major European nation does not contemplate the use of any alcohol in motor fuel in the event of war. Reports are that it has rejected the plea of automobile manufacturers and others to advance the octane ratings of various fuels on the grounds that in war time no alcohol would be available for that purpose, that the country's limited supply of tetraethyl lead would be used up in military fuels, and that commercial vehicles consequently should not be adapted to fuels of high antiknock value in face of the probability they would have to run on gasoline of relatively low antiknock value in time of war.

The Mining and Power Commission of the French Chamber of Deputies reported:

"So far as alcohol is concerned, wartime requirements for the explosives industry, for solvents, and for medicinal purposes would be so great that they would far exceed domestic production. This is borne out by the experience of the Great War, when French consumption amounted to between 5 and 6 million hectoliters, of which domestic output was able to supply one million hectoliters only. In time of national emergency alcohol would be far too valuable to be used as a motor fuel."

Compressed Gases as Motor Fuel.

Compressed gases are used as a motor fuel in the United States, Germany, and Italy. The development in Germany has turned toward the use of light-weight alloy cylinders attached to the motor vehicle to store the combustible gas under pressure. The gases used for motor fuel are coal gas, methane, ethane, propane, and butanes; they are compressed up to 4000 pounds per square inch, depending on the type of hydrocarbon.

Methane[4] has been derived from a number of sources, such as: natural refinery, and casinghead gases, and also may be available in vast quantities from sewage disposal plants. In the one plant in England where developments of utilization of methane from sewage are taking place, the amount of methane from sludge digestion amounts to about 1,350,000 cubic feet per day. Much of this is used to generate power and effect a saving of about $1,000,000 annually in fuel costs. It is estimated that 60,000,0000 cubic feet of methane are available daily in England and Wales which represents 3,750,000 horsepower hours.

The development of the use of compressed gases in the United States has taken place during the past few years. Propane and butane gases have been used for all classes of automotive equipment such as trucks, buses, agricultural tractors, and drag line shovels; between 10,000 and 12,000 units are reported to be in use in California. There are probably 25,000, or so, in use in the United States.

The sale of compressed gases for internal combustion engines showed an increase of 23 per cent during 1938 as compared to 1937, or an increase from 16,987,000 in 1937 to 20,914,000 gallons in 1938.

Hydrocarbon gases, whether derived from oil wells, gas wells, the distillation of crude oil, or the cracking process, may be separated into their components—methane, ethane, propane, butanes, and penatanes—by compression, absorption, distillation, and stabilization.

The greatest development in the use of compressed (up to 4500 pounds, gas fuel from coal gas, hydrogenation of coal and carbon monoxide, natural and refinery gases has been in Germany where it is estimated that over 1,300,000 barrels of gasoline were replaced by compressed gases during 1938. It is estimated over 25,000 German motor vehicles are using about 250,000 cylinders as storage tanks for compressed gases.

Motor vehicles are converted into the compressed gas type at a cost of from $150 to about $300 in Germany, depending on the size. The primary changes are as follows: (a) racks are installed to hold the steel cylinders; (b) the pressure reduction valve is installed to regulate the pressure drop between the cylinder and the motor; and (c) a special air-gas mixer is used in place of the gasoline carburetor.

At the present time[5] (December, 1939) the German Ministry of Transport has ordered that all commercial vehicles be converted to the use of gaseous fuels. Conversion of the heavier engined units is to take place first and later the lighter engined vehicles. The conversion provides an easy return to the use of liquids at any time. Further reduction of fuel consumption is taken care of by reducing the maximum speed of the motor cars to 25 miles per hour in cities and to 50 miles per hour elsewhere.

Italy has developed a natural gas field near Milan made up largely of methane which is being used as motor fuel. Some of the methane is frac-

[4] J. P. Lawrie, Chemical Products 2, No. 5, 121 (1939).

[5] O. Tokayer, Petroleum Press Service *6*, No. 41; 498-9 (1939).

tionated from coal gas. These gases are compressed at 3000 pounds per square inch into steel cylinders and distributed at filling stations which supply about four thousand buses and trucks in Italy. At present these hydrocarbon gases are replacing petroleum gasoline at the rate of about 2,500,000 barrels a year. It is expected that in a few years the use of methane from natural gas and coal carbonization will be several fold greater than it is at present. The use of the gas-burning motor vehicles in Germany and Italy has been subsidized by the governments through reduction of taxes and the extra tax levied on imported motor fuels. The cost of city gas, motor methane, and propane-butanes compared on a gallon of gasoline basis is 43, 41, and 61 cents, respectively.

It is estimated that in all Europe compressed gas will replace over 4,000,000 barrels of petroleum gasoline during the year 1939.

Producer Gas from Wood and Coal.

Other motor fuel substitutes in Europe include wood, coal, coke, and coal briquettes. Producer gas generated from wood, charcoal, and coal has been in use for stationary engines since 1900.[6] After the World War a steady development of "gasogene" motors took place for automobiles and tractors as well as stationary engines. The wood- and coal-burning motor buses and trucks have stoves mounted on the side of the car which may weigh a ton; other parts of the equipment consist of cooling pipes, a tank to collect condensed water, tar, and acids, a filtering agent, and a blower to draw the gas to the motor. These stoves are filled with either charcoal, wood, or charcoal and wood, or charcoal and coal mixtures. It takes from 10 to 20 minutes to warm up the engine to operating temperature.

The inefficiency of the wood-burning vehicle lies in the bulk and weight of the generating equipment and the consequent reduction of transport capacity. The inconvenience and delay in starting and also the delay necessitated by frequent cleaning of equipment do not appear favorable for the use of wood as a motor fuel except in case of necessity due to lack of other fuels.

Direct fabrication of wood-burning equipment for motor cars has been carried out and the vehicle is more expensive than the gasoline type. Many of the wood burners have been converted from the gasoline vehicle at a price ranging from $300 to $500, depending upon the size and service required.

Coal is not widely used as a "gasogene" fuel in Germany, but hard coal is said to be serving satisfactorily as a fuel for several Diesel-type railway engines operating on producer gas.

It is estimated that France, Germany, and Italy have replaced 475,000 barrels of gasoline with 500,000,000 pounds of wood. About 10,000 vehicles of the wood-burning type were in use in Europe during 1939.

With the beginning of the war, Sweden[7] prohibited the use of private cars, and now (1939) intends using charcoal producer-gas as an automotive fuel. Subsidies are granted as interest free loans for purchase or conversion of cars to producer gas vehicles. The army has been interested in running some of its cars on producer gas by way of experiment. The government is also subsidizing the production of suitable solid fuels.

---

[6] P. L. Hopper, National Resources Committee; Energy Resources and National Policy, p. 329 (1939).

[7] O. Tokayer, Petroleum Press Service *6*, No. 41; 498-9 (1939).

Ammonia, Hydrogen, Acetylene, and Coal Dust as Motor Fuels.

The desperate desire of nations to make themselves self-sufficient in substitute motor fuels is reflected in the experimental work going on with such substances as ammonia, hydrogen, and acetylene.

Synthetic ammonia has been used in Italy as a motor fuel substitute. The ammonia is dissociated to hydrogen and nitrogen by means of a so-called catalytic disintegrator, maintained at a temperature of 850-1100 degrees F. by the exhaust gases from the motor. Vaporization of the liquefied ammonia is accomplished by releasing the pressure in the storage tank and counteracting the refrigerating effect thus encountered by means of a disintegrator which utilizes the heat from the motor exhaust. In Cherso, Italy, a test using a Fiat passenger car developed 31 miles per hour in a road test. As a motor fuel the low heating value of ammonia does not lend itself to wide use. The high cost involved is another factor retarding its use.

Experiments on acetylene as a fuel indicated that it cannot do the full work of a gasoline engine and that thermal efficiency is highest with dilute air-gas mixtures.

Hydrogen as motor fuel in the form of compressed gas has also been tried. The results so far do not look very promising.

The methods of using coal dust as a motor fuel are slowly being worked out in Germany as a result of the further desire for self-sufficiency. The first coal-dust engine for "practical purposes" was ordered for a German power station in April, 1938. It has been suggested that a "great future" awaits the new engine since the fuel may be purchased at low cost, and also the coal used is indigenous to the country.

The development of the coal-dust engine dates back 50 years or so. Indications still show that the original difficulty of fuel feed has not been overcome since coal dust "cannot" be inducted into the motor in the same manner as liquid fuel. Special abrasive resistant cylinder walls, pistons, and rings are also necessary since the wear on ordinary steel cylinders (0.28 inches during 150 hours operation) becomes so great in a short time that the efficiency and operation of the motor are greatly impaired. Cast-iron cylinders showed 0.008 of an inch wear after 2 hours, 33 minutes. Chromium plated cast iron showed one-seventieth of this corrosion.

Petroleum Press Service Journal, December 30, 1938, stated that:

"It cannot yet be said with certainty whether the coal-dust engine will reach such a stage of development that it can be used for the propulsion of road vehicles, but it can be said with certainty that this will not be the case for the next ten years. The oil Diesel needed twenty-five years' development before it could be used for such purposes. The difficulties to be overcome in this respect by the coal-dust engine are considerably greater."

Conclusion.

Technologists of the different countries are developing their own resources in order to make themselves self-sufficient in motor fuels. Many types of combustible material are being used in motor vehicles, which are derived from such sources as natural gas, petroleum, coal carbonization, coal hydrogenation, hydrogenation of carbon monoxide, coal dust, coal briquettes, wood, alcohols, methanol and ethanol from fermentation and synthesis, acetylene, the cracking of ammonia, and hydrogen.

Many processes have been developed in the United States for the production of high antiknock motor fuel from petroleum. These processes are distillation of crude oil at atmospheric pressure, the cracking of nature's gaso-

line and heavy oils to high octane motor fuels, polymerization of olefins, alkylation of paraffin hydrocarbons, dehydrogenation and isomerization of paraffin hydrocarbons, and hydrogenation of oils in order to produce high octane gasoline.

The art is tending toward the production of single hydrocarbons or a group of three or four in order that the combustion in automotive engines may be controlled to a nicety instead of being satisfied with the motor fuels that are now in general use for pleasure cars, trucks, buses, and airplane engines.

Octane rating motor fuels of 100 and over are now being produced commercially for aviation use. It is predicted that 100 octane and higher motor fuel will be used for pleasure cars within five years or so. Nature never produced such type gasolines. As a matter of fact, these newer fuels now make the gasoline engine as efficient, if not more so, than the best Diesel engines of today.

It is the genius of the chemists and engineers who have commercialized and made available to society these newer fuels that permit greater speeds and greater lifting and carrying power of our airplanes and other motor vehicles.

MISCELLANEA OF INTEREST TO NAVAL ENGINEERS.

SMOOTH SPEED CONTROL OF WOUND-ROTOR MOTORS.—This article, by H. E. Larson, Industrial Department, General Electric, describes a new and smoother method of controlling speeds of wound-rotor motors. Reprinted from the September, 1940, issue of Power, published by McGraw-Hill Publishing Co., Inc., of 330 West 42nd St., New York, N. Y.

With special reactors, speed of wound-rotor motors can now be regulated from zero to 85 per cent synchronous with a torque range of from 15 to more than 100 per cent for a given speed.

Saturable-core reactors are now being used to control speed and torque of wound-rotor induction motors. These drives provide adjustable-varying speeds over wide ranges in a smooth stepless manner compared to coarse-stepped control by rotor resistance using bulky drum controllers or magnetic contactors.

Such a drive consists of a conventional wound-rotor induction motor with a saturable reactor in series with the stator windings and a small amount of permanent resistance connected in series with the rotor windings, Figure 1. Speed or torque of such a drive is controlled by adjusting reactor saturation.

A saturable-core reactor differs principally from the conventional iron-core reactor (with a single winding on an iron core) in that it has a saturating winding excited from a direct-current supply, in addition to the usual main alternating-current winding connected in series with the stator windings of the motor, Figure 1. These two reactor windings are arranged non-inductively with respect to each other so that no ac voltage is induced in the dc winding. By increasing the dc exciting current in the saturating winding, the reactance of the ac winding can be varied through a wide range such as 10 to 1 or even 15 to 1. In this manner, voltage applied to the induction motor is varied to produce a smooth change in motor torque and speed.

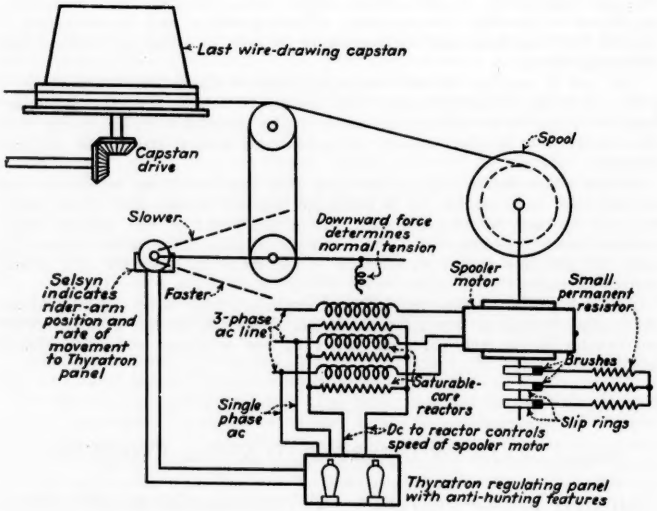


FIGURE 1.—AUTOMATIC SATURABLE-CORE-REACTOR CONTROL MAINTAINS CONSTANT TENSION IN WIRE BETWEEN WIRE-DRAWING MACHINE AND SPOOLER.

While no ac drive can equal the flexibility and other qualities of dc equipment, the system described gives smooth stepless control of accelerating torque, running torque or speed, decelerating or plugging torque. It has a speed range from standstill to approximately 85 per cent of synchronous speed, for 100 per cent rated motor torque. The torque range is from 15 to more than 100 per cent for a given speed.

AUTOMATIC REGULATION.

Automatic regulation is obtained more easily and with less expense than with rotor-resistance control. Starting control is greatly simplified, eliminating secondary accelerating contactors. Even timing relays for controlling the reactor excitation circuit during starting can be omitted by designing exciting circuits with high time constants. Improved efficiency is obtained compared with rotor-resistance control. Cost of motor, reactors, and control is usually less than that of other types of adjustable-varying-speed drives which use constant-speed ac motors with variable-speed equipment.

A typical 3-phase, wound-rotor, induction motor control using saturable-core reactors will include three single-phase reactors, a permanent resistance for the secondary circuit, a primary line contactor, thermal overload relays, a slide-wire rheostat for manual control, or an automatic means for adjusting the dc excitation. Independent control of accelerating and plugging torques can be obtained by using separate rheostats for the dc saturating winding with small transfer relays.

Typical speed-torque characteristics are shown in Figure 2. The shapes of these curves can be controlled to suit load requirements by proper selection of permanent secondary resistance. Figure 3 shows speed-torque curves of one of these drives for meeting the requirements of an induced-draft fan.

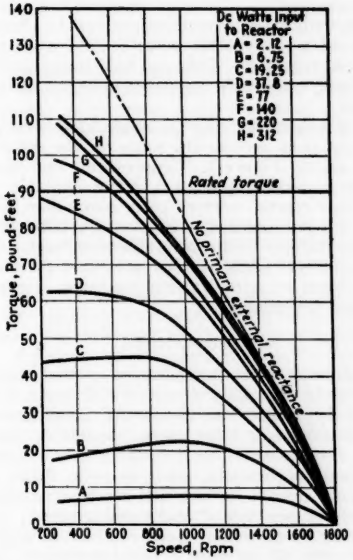


FIGURE 2.—SPEED-TORQUE CURVES FOR A 30 HP., 1800-RPM., WOUND ROTOR, INDUCTION MOTOR WITH 0.92-OHM EXTERNAL ROTOR RESISTANCE UNDER SATURABLE-CORE-REACTOR CONTROL.

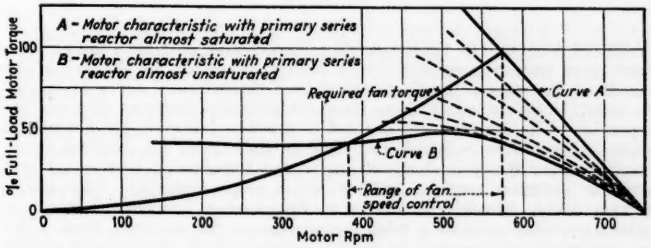


FIGURE 3.—SPEED-TORQUE CURVES OF A 200-HP., 750-RPM., WOUND-ROTOR MOTOR, UNDER SATURABLE-CORE-REACTOR CONTROL, DRIVING AN INDUCED-DRAFT FAN.

It should be understood that saturable-core-reactor control alone does not change the inherent adjustable-varying speed characteristic of a wound-rotor motor. When operating at reduced speed, whether with rotor resistance or with reactor control variations in load torque will cause changes in speed. These drives are, therefore, not comparable with adjustable-speed dc drives having shunt characteristics.

Adjustable speed with shunt characteristics can be obtained, however, by supplementing saturable-core-reactor control with a counter-electromotive-force exciter or speed regulator. This will hold the speed of the drive to any given preset value with reasonable regulation within a definite range, regardless of load torque.

The amount of dc power required for the saturable-core-reactor is small, ranging, for example, from zero to 312 watts for the entire speed and torque range of a 30-HP. motor, Figure 2. Copper-oxide rectifiers can be used for supplying excitation requirements when dc is not available.

Since saturable-core-reactor control costs more than conventional rotor-resistance control, it is not intended to supplant the latter in all cases. A few of many typical applications where saturable-core-reactor control should be considered when ac drives must be used are main drives of wire-drawing machines, spooler drives of wire-drawing machines, Figure 1, tension-reels of rolling mills, fans, and pumps.

APPLICATIONS.

One important general field of application is that requiring automatic-speed or torque control. In such instances, the dc input to the reactors may be easily regulated by phototubes, thyratrons, Amplidyne exciters, Selsyn transmitters with rectifiers, or other means capable of delivering dc power in small quantities in response to the commands of a regulatory system.

Some constant-speed applications, such as main drives of wire-drawing machines, require only smooth starting and accelerating characteristics from rest to approximately 80 per cent of final running speed. Accelerating from 80 per cent of running speed to full speed can be had without objectionable effects by short-circuiting all the rotor external resistance. This may be done by one accelerating contactor closing after full exciting current of the reactors has been reached. In this way, the constant-speed running losses of the drive are reduced to little more than those in a conventional wound-rotor motor with its slip rings short circuited.

APPLICATION OF FAN LAWS.—Performance data for a fan or pump under given operating conditions are readily calculated, by the use of fan laws, from the manufacturer's constant-speed characteristic curve or equivalent data. Applications of these laws are ordinary problems in ratio and proportion. The problems encountered in practice, however, are not always simple. Calculations in which two or even three laws are involved simultaneously are common, and the choice of the combination best suited to a particular situation may be baffling unless some systematic approach is adopted. G. A. Hendrickson, Dean of Engineering, Lawrence Institute of Technology, here presents a tabular statement of the fan laws from which the combination applying to a particular problem can be chosen mechanically. The use of the table is illustrated by an example. His article is here reprinted from the July, 1940 issue of Combustion, published by Combustion Publishing Co., 200 Madison Avenue, New York.

In dealing with fans it is customary to assume that the gas handled is incompressible when the changes in pressure and in volume are relatively small. Fan theory derived from this assumption is not essentially different from pump theory; consequently, distinguishing terms are unnecessary. The word pump is used here as a general term to include both fans handling gases and pumps handling liquids.

BASIS OF THE FAN LAWS.

The fan laws apply only to an operating condition in which the hydraulic efficiency of the pump remains constant as the rate of discharge varies. This efficiency may be defined as the ratio of the total head delivered by the pump to the sum of the total head delivered plus the head loss within the pump. That is,

$$e = h/(h + h_1) \quad \ldots\ldots (1)$$

where

e = hydraulic efficiency
h = increase in total head through pump, in feet
h_1 = head loss by turbulence within pump, in feet

The nature of the variations in h and h_1 may be conveniently studied in a simple system such as that illustrated by Figure 1. The head, h, represents simultaneously that delivered by the pump and that consumed in the system. It may, therefore, be concluded that if the loss within the pump and that in the system vary in the same proportion when the rate of circulation changes, the hydraulic efficiency of the pump, as indicated in Equation (1), remains constant. This condition is satisfied in any pump when the ratio of the velocity of flow to the peripheral velocity of the impeller is fixed.

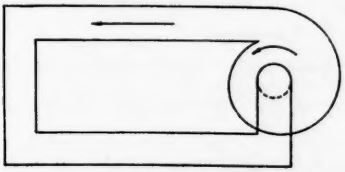


Fig. 1—Simple discharge system

The significance of this statement is illustrated in Figure 2, in which velocity diagrams for a centrifugal pump operating at capacities of approximately 100, 75, 50 and 25 per cent of normal load are shown at a, b, c and d, respectively. In these diagrams u is the peripheral velocity of the impeller, w the velocity of flow relative to the impeller channels, and v the absolute velocity of flow.

When the ratio v/u is constant, as in these diagrams, the relation which the pump presents to the flowing fluid is shown at e. Here the vanes are considered stationary and are placed in a straight instead of a circular arrangement. The relative angle which the fluid stream makes with each wall with which it is in contact is the same as that shown in the velocity diagrams. This "stationary likeness" which neglects the function of the pump as centrifugal machine, compares the flow through the pump to the flow past obstructions in stationary channels in which the loss of head is proportional to the square of the velocity of flow.

The situation is the same in the actual impeller. When the fluid stream strikes each wall at a constant relative angle, the turbulent loss at that wall is proportional to the square of the velocity of flow. Since h, the loss of head in a given discharge system of the type considered, is proportional to the square of the velocity of flow in any condition, the ratio h_1/h is constant when the velocity ratio v/u is fixed, and under this condition the hydraulic efficiency does not change.

Each of the statements of proportionality and constant ratios as employed in the foregoing discussion of the necessary condition for a constant hydraulic efficiency, is a simple fan law. For example, the condition that the velocity ratio v/u is constant, is equivalent to the statement that the discharge rate varies directly as the rotative speed. This is evident when it is noted that v can be expressed in terms of the discharge rate and u in terms of rotative speed.

Other statements can be similarly transformed, and all of the fan laws can be derived from them with the aid of a few commonly used physical laws. It is not the purpose here to make these derivations. The example given indicates that they arise from any operating condition in which the hydraulic efficiency remains constant.

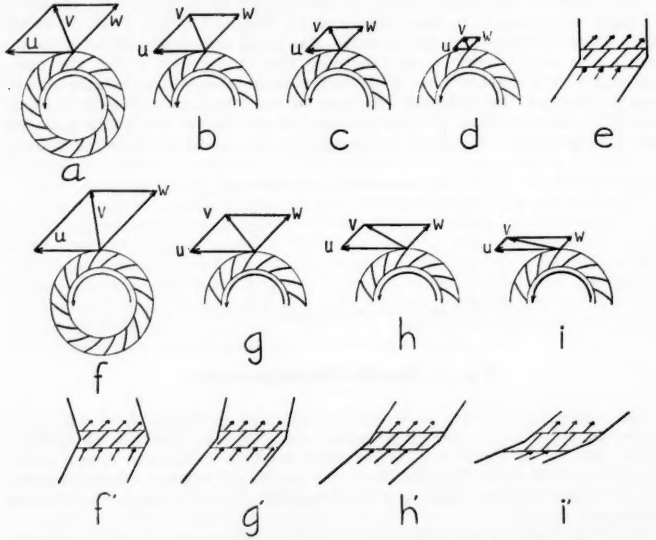


Fig. 2—Pump velocity diagrams and flow characteristics

SCOPE OF THE FAN LAWS.

At this point some attention to operation with varying hydraulic efficiency is desirable. The constant-speed characteristic curve is of particular interest. Figure 3 shows such a curve, kfaghij, and the constant efficiency curve, abcdo, of the foregoing discussion is shown for comparison.

In this diagram the increase in pressure, p, between the inlet and the outlet of the pump is plotted against the rate of discharge c. Each plotted point bears the same reference letter as the corresponding velocity diagram in Figure 2, where the effect of changing the velocity of flow, v, while the peripheral velocity u is maintained constant, is represented in f, g, h and i, and their accompanying "sationary likenesses" f', g', h' and i' are drawn for 125, 75, 50 and 25 per cent of normal discharge, respectively.

Each of these diagrams shows a different value of the velocity ratio v/u. The pump operating with v/u constant at any one of these values produces another curve in which the hydraulic efficiency is constant but different from

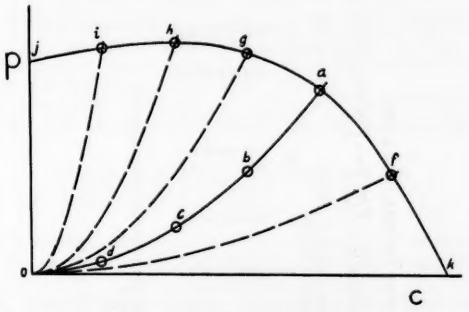


Fig. 3—Constant-speed characteristic and constant-efficiency curves

that of the original curve abcdo. These curves are shown in the broken lines og, oh and oi of Figure 3. Each point on the constant-speed characteristic kfghij has a constant hydraulic efficiency curve passing through it to the origin o.

The variation in efficiency from one point to another, not on the same efficiency curve, cannot be predicted accurately, and it is impossible to use the fan laws between two such points. A statement of the pump performance must be available from the manufacturer at each rating used with the fan laws. These data are usually given in the form of a constant-speed characteristic curve or a table of performances at different ratings for some standard fluid density and rated speed. This specification ordinarily differs from the operator's requirements, and corrections must be made through the fan laws.

FAN LAWS.

Numerous fan laws may be written. Ten or twenty of the most common are usually stated, and corrections are made through the necessary combination chosen from those given. This procedure is greatly simplified if it is observed that all corrections may be expressed in the general form.

TABULAR STATEMENT OF THE FAN LAWS

Values of the exponents n in the equation $\frac{n_2}{n_1} = \left[\frac{m_2}{m_1}\right]^{x_{mn}} \left[\frac{d_2}{d_1}\right]^{y_{mn}} \left[\frac{s_2}{s_1}\right]^{z_{mn}}$

Values of the exponent x_{mn} when d is constant, s is constant and x is variable

$m \rightarrow$ / $n \downarrow$	c	h	N	P	p	v	W
c	1	1/2	1	1/3	1/2	1	1
h	2	1	2	2/3	1	2	2
N	1	1/2	1	1/3	1/2	1	1
P	3	3/2	3	1	3/2	3	3
p	2	1	2	2/3	1	2	2
v	1	1/2	1	1/3	1/2	1	1
W	1	1/2	1	1/3	1/2	1	1

Values of the exponent y_{mn} when $d = kb/T$, s is constant and x is constant

$m \rightarrow$ / $n \downarrow$	c	h	N	P	p	v	W
c	0	0	0	−1/3	−1/2	0	−1
h	0	0	0	−2/3	−1	0	−2
N	0	0	0	−1/3	−1/2	0	−1
P	1	1	1	0	−1/2	1	−2
p	1	1	1	1/3	0	1	−1
v	0	0	0	−1/3	−1/2	0	−1
W	1	1	1	2/3	1/2	1	0

Values of the exponent z_{mn} when d is constant, $s = kvA$ and x is constant

$m \rightarrow$ / $n \downarrow$	c	h	N	P	p	v	W
c	0	2	3	4/3	2	2	0
h	−4	0	2	−10/3	0	0	−4
N	−3	−1	0	−3	−1	−1	−3
P	−4	2	5	0	2	2	−4
p	−4	0	2	−4/3	0	0	−4
v	−2	0	1	−2/3	0	0	−2
W	0	2	3	10/3	2	2	0

A = Outlet area of fan, sq ft
b = barometric pressure, in. Hg
c = discharge rate, cfm
d = fluid density, lb per cu ft
h = head, ft
N = rpm
P = horsepower
p = pressure increase between fan inlet and outlet, in. H_2O
s = fan size, in a unit of length
T = absolute temperature, F
v = velocity of flow, ft/sec
W = weight of fluid pumped, lb per hr

$$\frac{n_1}{n_2} = \left[\frac{m_1}{m_2}\right]^{x_{mn}} \left[\frac{d_1}{d_2}\right]^{y_{mn}} \left[\frac{s_1}{s_2}\right]^{z_{mn}} \quad \ldots\ldots\ldots\ldots (2)$$

where

n = any item of operating data; capacity, c; head, h; etc., which must be corrected to a new operating condition
m = any other item of operating data for which both corrected and uncorrected values are known
d = fluid density, lb per cu ft
s = fan size, in a unit of length

Values of the exponents x_{mn}, y_{mn} and z_{mn} are chosen from the accompanying table. They are found in the row m and in the column n. Subscripts 1 and 2 indicate the two points at the same hydraulic efficiency between which correction is made.

For use with gases, when density is given in terms of temperature and pressure, Equation (2) may be written in a more convenient form,

$$\frac{n_2}{n_1} = \left[\frac{m_2}{m_1}\right]^{x_{mn}} \left[\frac{b_2}{b_1}\right]^{y_{mn}} \left[\frac{T_2}{T_1}\right]^{-y_{mn}} \left[\frac{s_2}{s_1}\right]^{z_{mn}} \quad \ldots\ldots\ldots (3)$$

Over two hundred equations involving the different variables and combinations of the different variables in the tabulated statement of the fan laws, may be written directly in the form of Equation (3), and others may be derived. Some of these equations are simple physical laws, but the greater number are usable fan laws. The reader will find many possibilities.

APPLICATION OF THE FAN LAWS.

Use of the table is illustrated in the following example:

A No. 10 Sirocco fan with double inlet boxes and two-thirds double width delivers 98,830 cfm of air at 8-inch water static pressure and 478 RPM. when the atmospheric pressure is 29.92 inches Hg and the temperature 70 F. What would be the discharge capacity at zero F with the same static pressure and the same atmospheric pressure?

A new capacity is asked. Use c for n in Equation (3). The static pressure is known at both points. Use p for m. Then write Equation (3) as,

$$\frac{c_2}{c_1} = \left[\frac{p_2}{p_1}\right]^{x_{pc}} \left[\frac{b_2}{b_1}\right]^{y_{pc}} \left[\frac{T_2}{T_1}\right]^{-y_{pc}} \left[\frac{s_2}{s_1}\right]^{z_{pc}} \quad \ldots\ldots\ldots (4)$$

With exponents chosen from the table this equation becomes,

$$\frac{c_2}{c_1} = \left[\frac{p_2}{p_1}\right]^{\frac{1}{2}} \left[\frac{b_2}{b_1}\right]^{-\frac{1}{2}} \left[\frac{T_2}{T_1}\right]^{\frac{1}{2}} \left[\frac{s_2}{s_1}\right]^{2} \quad \ldots\ldots\ldots\ldots (5)$$

Since $p_1 = p_2$, the ratio $(p_1/p_2)^{x_{pc}}$ is unity whatever the value of x_{pc}, and this exponent need not even be read from the table for this simple problem. A similar statement is true for the ratio s_2/s_1. Equation (4) would simply be written

$$c_2/c_1 = (T_2/T_1)^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Solution for c_2 gives

$$c_2 = c_1 \sqrt{T_2/T_1}$$
$$= 98{,}830 \sqrt{(460 + 0)/(460 + 70)}$$
$$= 92{,}070 \text{ cfm} \quad \ldots\ldots (7)$$

The fan would deliver 92,070 cfm of air at zero F and 29.92-inches Hg against a static pressure increase of 8-inch H_2O.

The rotative speed at this new capacity can now be computed by using N for n and p for m in Equation (3). This gives

$$\frac{N_2}{N_1} = \left[\frac{p_2}{p_1}\right]^{xpN} \left[\frac{b_2}{b_1}\right]^{ypN} \left[\frac{T_2}{T_1}\right]^{-ypN} \left[\frac{s_2}{s_1}\right]^{zpN} \quad \ldots\ldots (8)$$

or

$$\frac{N_2}{N_1} = \left[\frac{p_2}{p_1}\right]^{\frac{1}{2}} \left[\frac{b_2}{b_1}\right]^{-\frac{1}{2}} \left[\frac{T_2}{T_1}\right]^{\frac{1}{2}} \left[\frac{s_2}{s_1}\right]^{-1} \quad \ldots\ldots (9)$$

which becomes

$$\frac{N_2}{N_1} = \left[\frac{T_2}{T_1}\right]^{\frac{1}{2}} \quad \ldots\ldots (10)$$

or

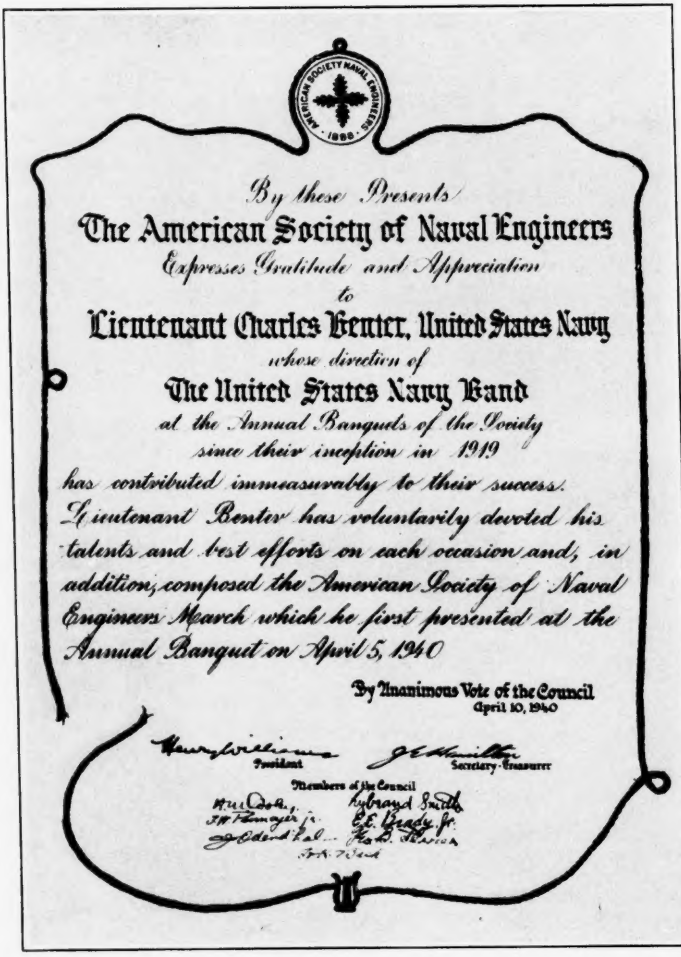
$$N_2 = N_1 \sqrt{T_2/T_1}$$
$$= 478 \sqrt{460/(460 + 70)}$$
$$= 445.3 \text{ rpm} \quad \ldots\ldots (11)$$

If the original problem had asked for the capacity at a given static pressure p_2 different from 8 inches the new capacity would be found from Equation (5) if the ratio p_2/p_1 is substituted in that equation simultaneously with the ratio T_2/T_1.

In a similar manner the horsepower, weight of fluid pumped or any other item of performance data may be calculated from the manufacturer's data and the accompanying tabulated statement of the fan laws.

OPTICAL PLASTIC.—The following note from the 1940 Worcester meeting, The American Society of Mechanical Engineers, is reprinted from the August, 1940, issue of Mechanical Engineering, published by the American Society of Mechanical Engineers, 20th and Northampton Sts., Easton, Pa.

During an inspection trip to the Norton Company by members attending the 1940 spring meeting of The American Society of Mechanical Engineers in Worcester, Mass., the company's research engineers showed them a new type of plastic material which can be used for optical purposes. This non-moldable resin can be readily sawed, drilled, turned, and even ground and polished on opticians' laps. It does not exhibit true plastic flow under heat and pressure but may be bent to shape at 160 C. The tensile strength of the material at room temperature is 8000 to 10,000 psi, and the hardness is 60-62 on a Rockwell C scale with a 68-kg load and ⅛-inch ball for 15 seconds. Its stability to sunlight and ultraviolet light is excellent. Non-breakable eyeglasses are now being produced from this material by an optical company on an experimental basis.


AMERICAN SOCIETY NAVAL ENGINEERS
1888
By these Presents
The American Society of Naval Engineers
Expresses Gratitude and Appreciation
to
Lieutenant Charles Benter, United States Navy
whose direction of
The United States Navy Band
at the Annual Banquets of the Society
since their inception in 1919
has contributed immeasurably to their success.
Lieutenant Benter has voluntarily devoted his
talents and best efforts on each occasion and, in
addition, composed the American Society of Naval
Engineers March which he first presented at the
Annual Banquet on April 5, 1940
By Unanimous Vote of the Council
April 10, 1940
President
Secretary-Treasurer
Members of the Council

ASSOCIATION NOTES.

At a meeting of the Council of the Society on August 1, 1940, a plaque, reproduced on the opposite page, and a music case were presented to Lieutenant Charles Benter, U. S. Navy, in carrying out the Council's decision mentioned in the Association Notes in the May, 1940, issue.

MINUTES OF ANNUAL MEETING, TUESDAY, OCTOBER 1, 1940.

The meeting was called to order at 4:15 p. m. by the President, Captain Henry Williams, U. S. N.

Present: President Captain Henry Williams, U. S. N., Secretary-Treasurer Commander J. E. Hamilton, U. S. N., Captain J. A. Furer, U. S. N., Captain Lybrand P. Smith, U. S. N., Captain H. M. Cooley, U. S. N., Captain P. B. Eaton, U. S. C. G., Commander F. W. Pennoyer, Jr., U. S. N., Commander David Clark, U. S. N., Lieut. Commander P. D. Gold, U. S. N., Rear Admiral S. M. Robinson, U. S. N., Lieut. Commander C. Gibson Ford, U. S. N. R., Lieut. Commander M. R. Williams, U. S. N., Lieut. Commander Frederick W. Beltz, U. S. N., Commander T. J. Bay, U. S. N., Commander Louis Dreller, U. S. N., Lieut. R. K. James, U. S. N., Commander H. N. Perham, U. S. C. G., Mr. A. Campbell, Mr. H. K. Beck, Mr. C. L. Frear.

Congratulations to the President: Captain H. M. Cooley, U. S. N., on behalf of the Society offered congratulations to the President on his attainment of the rank of Rear Admiral and presented him with his flag. Rear Admiral Williams expressed his warm appreciation of the action of the Society.

The reading of the Minutes of the last previous meeting of the Society was waived by vote of the membership.

In a very short address the President expressed his appreciation of the honor of having been the leader of the Society for the year. He stated that, in accordance with a suggestion made at the last previous meeting, he had appointed a committee composed of Captain J. M. Irish, U. S. N., Captain C. A. Jones, U. S. N., and Commander J. E. Hamilton, U. S. N., to confer with a like committee of the Society of Naval Architects and Marine Engineers relative to possible closer association of the two societies. He expressed his thanks to all those who had worked with him for the success of the Society.

Report of the Secretary-Treasurer: The Secretary-Treasurer submitted a preliminary report of the condition of the Society. He stated that he had been appointed by the Council on April 22, 1940, to fill the unexpired term of Lieut. Commander Guy E. Chadwick, who resigned consequent upon detachment from duty in Washington. He reported the action of the Council in tendering to Lieutenant Benter, Leader of the Navy Band, a testimonial in the form of resolutions and a music bag in recognition of his long service in rendering music for banquets of the Society, which was of so much assistance in their success. He reported that the banquet of the Society in 1940 was probably the most enjoyable of any yet held; that a souvenir in the form of a replica of the Society Seal was given each guest, and that financially there was a net gain of $758.39. He reported a gain of 245 in membership thus far during the year, with a gain of 229 subscriptions and 4¼ pages of advertisements. A total of $8400 approximately was reported in the Society's checking account.

Investment: On motion of Mr. Beck, the Council was authorized to invest such of the surplus cash on hand as was deemed wise.

NOMINATIONS TO OFFICES FOR THE CALENDAR YEAR 1941.

A committee composed of Rear Admiral S. M. Robinson, U. S. N., Captain J. A. Furer, U. S. N., and Commander Frederick W. Pennoyer, Jr., U. S. N., appointed by the President in accordance with the By-Laws, presented the following nominations for offices of the Society for the calendar year 1941:

For President:
Captain C. A. Jones, U. S. N.

For Secretary-Treasurer:
Commander J. E. Hamilton, U. S. N.
Lieut. Commander E. C. Forsyth, U. S. N.

For Member of Council:
Commander Thomas J. Bay, U. S. N.
Captain Walter W. Webster, U. S. N.
Captain Halford R. Greenlee, U. S. N.
Commander Louis Dreller, U. S. N.
Captain E. D. Almy, U. S. N.
Lieut. Commander Leroi B. Blaylock, U. S. N.
Captain Edward L. Cochrane, U. S. N.
Commander Norborne L. Rawlings, U. S. N.
Commander Ellis Reed-Hill, U. S. C. G.
Lieut. Commander E. H. Thiele, U. S. C. G.
Mr. W. S. Newell.
Mr. W. E. Blewett, Jr.
Mr. Lawrence Y. Spear.
Mr. George W. Codrington.

The President called for any further nominations desired. None was offered. Nominations were then closed by vote.

Amendments to By-Laws: The Secretary-Treasurer presented the following amendments to the By-Laws necessitated and made desirable by the amalgamation of the Bureaus of Engineering and Construction and Repair and the abolition of the Construction Corps of the Navy by legislation:

Amendment No. 1. Article 5, line 3, change "two" to "three" and delete all of line 4 and "Navy" in line 5, so that the first sentence of Article 5 will read:

"The Council shall be composed of nine members, two of whom shall be the President and the Secretary-Treasurer of the Society; of the remaining members, at least three shall be line officers of the regular United States Navy, at least one an officer of the United States Coast Guard and at least two civilians."

Amendment No. 2. Article 19, lines 2 and 3, delete "Engineering" and substitute "Ships." Lines 2 and 3, delete "The Chiefs of all material bureaus—that is." Lines 3 and 4, delete "The Chief of the Bureau of Construction and Repair." Line 5, after "Aeronautics," insert "The Assistant Chief of the Bureau of Ships," so that the first sentence of Article 19 will read:

"The Secretary of the Navy, the Assistant Secretary of the Navy, the Chief of the Bureau of Ships, the Chief of the Bureau of Ordnance, the Chief of the Bureau of Yards and Docks, the Chief of the Bureau of Aeronautics, the Assistant Chief of the Bureau of Ships, and the Engineer-in-Chief of the United States Coast Guard—all ex-Presidents of the Society, all prize essayists, and such other persons as the Society may elect shall be Honorary Members."

Voted to offer the amendments to the membership.

Banquet, 1941: It was the consensus of the meeting that a banquet be held during 1941. The President appointed Captain C. A. Jones, Chairman of a preliminary committee for selection of a date and making necessary arrangements.

Vote of Thanks to President: On motion of Captain Cooley, a rising vote of thanks was tendered to Captain Henry Williams for his excellent work as President of the Society during the year. The President responded, expressing his appreciation.

Society Insignia: Lieut. Commander Ford, U. S. N. R., moved that the Council be authorized to make arrangements for a button or other insignia for the Society. The motion was seconded by Rear Admiral Robinson and carried by vote.

Adjournment: The meeting adjourned at 4:48 p. m.

MINUTES OF MEETING OF COUNCIL, OCTOBER 17, 1940.

The meeting was called to order at 2:03 p. m., by President Rear Admiral Henry Williams.

Present: President Rear Admiral Henry Williams, Secretary-Treasurer Commander J. E. Hamilton, Captain Lybrand P. Smith, Commander E. E. Brady, Captain H. M. Cooley, Commander C. J. Odend'hal, U. S. Coast Guard. Letters were received from

Commander F. W. Pennoyer, Jr., and Mr. H. K. Beck stating their inability to be present on account of absence from the city.

Society Insignia: The Secretary-Treasurer was authorized to procure 1000 buttons, a replica of the Society seal, and offer them for sale at 50 cents each to the membership.

Investment of Funds: Various possible investments of surplus funds were discussed, the Secretary-Treasurer reporting that the bank is of opinion that commercial investments of both stock and bonds are most uncertain at this time and that Government securities will yield only about 1½%. He was authorized to place in savings bank accounts in $1000.00 lots funds which in his discretion could be spared from working capital.

Membership Campaign: The matter of a membership campaign was discussed and it was voted that this will be confined at this time to a letter from the President to officers in the Bureau of Ships who are not members.

Editorial Policy: The matter of editorial policy was discussed.

Publication of Notices of Meetings of Other Societies, Etc.: It was decided that the publication of notices of meetings, etc., of other societies and organizations, of general interest to the membership, shall be left to the discretion of the Secretary-Treasurer.

Adjournment: The meeting adjourned at 3:10 p. m.

Lapel buttons to be worn by members of the Society will be ready for mailing, on order, shortly after this issue appears. The price to members is 50 cents, postpaid, per button. The design is that of the Society insignia shown on the cover of the JOURNAL just above the month of issue. The leaf device, which is that of the old Engineer Corps, the letters and the outside circumference are in red enamel on a Roman gold background. Diameter one-half inch. An order blank for lapel buttons will be found on the last page of the Association Notes.

In compliance with the resolution of the Council, the Secretary-Treasurer has transferred $4000 from the Society's checking account to savings accounts drawing two per cent interest as follows:

American Security and Trust Company	$1000
Washington Loan and Trust Company	1000
Union Trust Company	1000
National Savings and Trust Company	1000

NEW MEMBERS.

The following have joined the Society since the publication of the August, 1940, JOURNAL:

NAVAL.

Bonin, R. A., Lieutenant, U. S. Navy.

Cressy, M. S., Divisional Manager, Calco Chemical Division, American Cyanamid Co., Bound Brook, N. J.

Erdner, Lewis E., Machinist, U. S. Navy.

Gibson, Scott K., Lieutenant, U. S. Navy.

Hamilton, M. J., Lieutenant, U. S. Navy.

James, Ralph K., Lieutenant, U. S. Navy.

Mudge, W. A., Lieut. Commander, U. S. N. R., Assistant Director, Technical Service, International Nickel Co., 67 Wall St., New York, N. Y.

Myers, Donald J., Machinist, U. S. N.

W. Burton Piersoll, 503 Rockavon Road, Narberth, Pa.

Rawlings, N. L., Commander, U. S. Navy.

Reed-Hill, Ellis, Commander (E), U. S. C. G.

Tinkham, R. R., Captain, U. S. C. G.

Webster, Walter W., Captain, U. S. N.

Zerban, Alexander H., Lieutenant, U. S. N. R., 536 E. Foster Ave., State College, Pa.

CIVIL.

Emmett, Charles G., Apartment C-11, James Garfield Building, Presidential Gardens, Alexandria, Va.

Gill, Stanley, Taylor Forge and Pipe Works, Philadelphia, Pa. Residence, R. F. D. No. 1, Morristown, N. J.

Lasciak, Charles, Design Division, Computing Section, Bureau of Ships, Navy Department, Washington, D. C.

Luckenbuch, J. Lewis, President, American Bureau of Shipping, 24 Old Slip, New York, N. Y.

Staller, Alfred W., Factory Manager, Crescent Wire and Cable Company, Trenton, N. J.

Tomalin, Paul G., U. S. Coast Guard Headquarters, Washington, D. C.

ASSOCIATE.

McNair, Norman J., Inspector, Office of Inspector of Naval Material, Chicago. Residence, 1119 Maple Ave., Evanston, Ill.

Seither, A. B., Jr., District Manager, Taylor Forge and Pipe Works, 942 Broad St. Station Building, Philadelphia.

PRESS RELEASE OF POSSIBLE INTEREST TO MEMBERS OF THE SOCIETY

RELEASE ON "WHO'S WHO IN ENGINEERING," FIFTH EDITION, OCTOBER 10, 1940.

Engineers throughout the country will soon receive material, questionnaires and previously printed records bearing on the new (5th) edition of "Who's Who in Engineering." This work is being revised under the editorship of Dr. W. S. Downs, with qualifications established by a committee of the engineering profession, composed as follows: Andrey A. Potter, Chairman, Dean, Schools of Engineering, Purdue University; Colonel L. B. Lent, Vice-Chairman, Executive Secretary, American Engineering Council; Frederic L. Bishop, Secretary, Society for Promotion of Engineering Education; C. E. Davies, Secretary, American Society of Mechanical Engineers; H. H. Henline, National Secretary, American Institute of Electrical Engineers; T. Keith Legare, Secretary, National Council, State Boards of Engineering Examiners; A. B. Parsons, Secretary, American Institute of Mining and Metallurgical Engineers; George T. Seabury, Secretary, American Society of Civil Engineers; Stephen L. Tyler, Secretary,

American Institute of Chemical Engineers; John A. C. Warner, Secretary and General Manager, Society of Automotive Engineers.

The publishers have been favorably known over a long period. "Who's Who in Engineering" has proved its worth and is commended to the careful consideration of the individual engineer, particularly as ready reference to personal professional data is now of pressing importance in all phases of national defense.